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**A FLEXIBLE HYPERSONIC VEHICLE MODEL
DEVELOPED WITH PISTON THEORY (PREPRINT)**

Michael W. Oppenheimer, Torstens Skujins, David B. Doman, and Michael A. Bolender

**Control Design and Analysis Branch
Structures Division**

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A Flexible Hypersonic Vehicle Model Developed With Piston Theory

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I. Abstract

For high Mach number flows, $M \geq 4$, piston theory has been used to calculate the pressures on the surfaces of a vehicle. In a two-dimensional inviscid flow, a perpendicular column of fluid stays intact as it passes over a solid surface. Thus, the pressure at the surface can be calculated assuming the surface were a piston moving into a column of fluid. In this work, first-order piston theory is used to calculate the forces, moments, and stability derivatives for longitudinal motion of a hypersonic vehicle. Piston theory predicts a relationship between the local pressure on a surface and the normal component of fluid velocity produced by the surface's motion. The advantage of piston theory over other techniques, such as Prandtl-Meyer flow, oblique shock, or Newtonian impact theory, is that unsteady aerodynamic effects can be included in the model. Prandtl-Meyer flow and oblique shock theory are utilized to provide flow properties over the surfaces of the vehicle. These flow properties are used to determine the steady forces and moments and are also included in the unsteady flow calculations. Thus, this work utilizes a combination of Prandtl-Meyer flow, oblique shock, and piston theory to calculate forces and moments. The unsteady effects, considered in this work, include perturbations in the linear velocities and angular rates, due to rigid body motion. A flexible vehicle model is developed to take into account the aeroelastic behavior of the vehicle. The vehicle forebody and aftbody are modelled as cantilever beams fixed at the center-of-gravity. Piston theory is used to account for the changes in the forces and moments due to the flexing of the vehicle. Piston theory yields an analytical model for the longitudinal motion of the vehicle, thus allowing design trade studies to be performed while still providing insight into the physics of the problem.

II. Introduction

In the 1980's, the National Aerospace Plane (NASP) program commenced, with its goal being a feasibility study for a single-stage to orbit (SSTO) vehicle, which was reusable and could take off and land horizontally. The NASP was to be powered by a supersonic combustion ramjet (scramjet) engine. Although this program was cancelled in the 1990's, a great deal of knowledge was gained and it spawned future programs, including the hypersonic systems technology program (HySTP), initiated in late 1994, and the NASA X-43A. The HySTP's goal was to transfer the accomplishments of the NASP program to a technology demonstration program. This program was cancelled in early 1995. The NASA X-43A set new world speed records in 2004, reaching Mach 6.8 and Mach 9.6 on two separate occasions with a scramjet engine. These flights were the culmination of NASA's Hyper-X program, with the objective being to explore alternatives to rocket power for space access vehicles.

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With renewed interest in space operations worldwide, there is an interest in hypersonic aerodynamics research. The scramjet engine will likely play a major role in future hypersonic vehicles. Unlike a conventional turbojet engine, a scramjet engine does not use high speed turbomachinery to compress the air before it reaches the combustor. Instead, it relies upon the rise in pressure across oblique shock waves located in front of the inlet. Furthermore, the flow through the entire engine is supersonic in contrast to a ramjet, where the flow speeds are subsonic through the combustor. On configurations like the NASP and X-43A, the underside of the airframe must function as the air inlet mechanism and the exhaust nozzle. Therefore, integration of the airframe and engine are critical to success of a scramjet powered vehicle.

Scramjets could be used as part of a multi-stage launch vehicle that would include multiple propulsion systems to perform a mission. The factor driving research towards scramjets and away from rockets is cost; scramjets would substantially lower costs because it is an airbreathing engine. Airbreathing engines don't require oxidizer to be carried by the vehicle, hence increasing the payload and reducing the quantity of fuel carried.

Unsteady aerodynamics are a phenomenon that must be considered in the development and optimization of future hypersonic vehicles. The combined effects of a slender flexible vehicle travelling at high speeds and subjected to large forces may lead to significant unsteady aerodynamic effects. Hence, understanding the concepts and consequences of time-dependent aerodynamic flows is critical to the successful development of this type of vehicle.

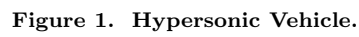
Piston theory is a technique that has been used for years to determine the pressure distributions on an airfoil/vehicle, when the Mach number is sufficiently high. Lighthill¹ discussed the application of piston theory on oscillating airfoils some 50 years ago. Ashley and Zartarian² discuss piston theory while providing a number of examples of the application of piston theory to specific problems. More recently, Tarpley³ discussed the computation of stability derivatives for a caret-wing waverider using piston theory, which requires the analysis of unsteady flow over the vehicle. Piston theory allows the inclusion of unsteady aerodynamic effects in the model and a closed form solution can be found for these unsteady effects.

In this work, piston theory is applied to a hypothetical 2-dimensional hypersonic vehicle powered with a scramjet. This work uses first-order piston theory to compute unsteady effects behind shock waves and expansion fans. A recent study⁴ revealed that this method of computing unsteady aerodynamic effects delivered highly accurate results when compared to computational fluid dynamics solutions and higher order piston theory models. This paper builds on previous work⁵ by incorporating a flexible vehicle model and determining the perturbations to forces and moments due to flexibility.

In Section III, the vehicle analyzed in this work is described, while the steady forces and pressures on the vehicle's surfaces are provided in Section IV. The unsteady effects due to the aerodynamic control surfaces are included in Section V, the total rigid body forces and moments are discussed in Section VI, while the aeroelastic model is developed in Section VII. Results are provided in Section VIII, conclusions are given in Section IX, and Appendix A contains detailed calculations for many of the flexible stability derivatives.

III. HSV Model

Figure 1 shows the 2-dimensional hypersonic vehicle considered in this work.⁶ The longitudinal force and moment analysis is taken as unit depth into the page. The vehicle consists of 4 surfaces: an upper surface (defined by points cf) and three lower surfaces (defined by points cd, gh, and ef). All pertinent lengths and dimensions are in units of feet and degrees, respectively. The total length of the vehicle is $L = 100ft$ and the notation for lengths is L_f = length of the forebody, L_n = length of the engine nacelle, L_a = length of the aftbody, L_e is the length of the elevator, L_c is the length of the canard, \bar{x}_f is the distance from the C.G. to the front of the vehicle, \bar{x}_a is the distance from the C.G. to the rear of the vehicle, x_{elev} and z_{elev} are the distances from the C.G. to the midpoint of the elevator in the x and z directions, respectively, x_{canard} is the distance from the C.G. to the midpoint of the canard, and h_i is the engine height. The vehicle dimensions


$$\begin{aligned} L &= 100 \text{ ft} \\ L_f &= 47 \text{ ft} \\ L_a &= 33 \text{ ft} \\ L_n &= 20 \text{ ft} \\ L_e &= 17 \text{ ft} \\ L_c &= 10 \text{ ft} \\ \bar{x}_f &= 55 \text{ ft} \\ \bar{x}_a &= 45 \text{ ft} \\ x_{elev} &= 30 \text{ ft} \\ z_{elev} &= 3.5 \text{ ft} \\ h_i &= 3.25 \text{ ft} \\ x_{canard} &= 40 \text{ ft} \end{aligned} \tag{1}$$
$$\begin{aligned}\tau_{1,U} &= 3^\circ \\ \tau_{1,L} &= 6^\circ \\ \tau_2 &= 14.41^\circ\end{aligned}\tag{2}$$
$$\begin{aligned} Mass &= 300 \frac{slug}{ft} \\ J_{yy} &= 500,000 \frac{slug-ft^2}{ft} \end{aligned} \quad (3)$$

and the mean aerodynamic chord (\bar{c}) and planform area (S) are defined as

$$\begin{aligned}\bar{c} &= L \\ S &= L^2\end{aligned}\tag{4}$$

The goal is to apply piston theory to this 2-dimensional vehicle geometry to determine the pressure distribution on the surfaces of the vehicle, which, in turn, can be used to evaluate the forces and moments. The pressure on the face of a piston moving into a column of perfect gas is²

$$\frac{P}{P_\infty} = \left(1 + \frac{\gamma - 1}{2} \frac{V_n}{a_\infty}\right)^{\frac{2\gamma}{\gamma - 1}}\tag{5}$$

where the subscript " ∞ " refers to the steady flow conditions past the surface, V_n is the velocity of the surface normal to the steady flow, a_∞ is the freestream speed of sound, and P is the surface pressure. Taking the binomial expansion of Eq. 5, to first order, produces

$$\frac{P}{P_\infty} = 1 + \frac{2\gamma}{\gamma - 1} \frac{\gamma - 1}{2} \frac{V_n}{a_\infty} = 1 + \frac{\gamma V_n}{a_\infty}\tag{6}$$

Multiplying through by P_∞ and using the perfect gas law ($P = \rho RT$) and the definition of the speed of sound ($a^2 = \gamma RT$) yields the basic result from first-order linear piston theory

$$P = P_\infty + \rho_\infty a_\infty V_n\tag{7}$$

where γ is the ratio of specific heats and R is the gas constant. The infinitesimal force, on an elemental area, due to the pressure is given by

$$d\mathbf{F} = -Pd\mathbf{A}\mathbf{n}\tag{8}$$

where dA is a surface element and \mathbf{n} is the outward pointing normal. Substituting Eq. 7 into Eq. 8 yields

$$d\mathbf{F} = (-P_\infty - \rho_\infty a_\infty V_n) d\mathbf{A}\mathbf{n}\tag{9}$$

The normal velocity can be computed by taking the dot product of the flow velocity over a surface and the outward pointing normal for that surface. Hence, Eq. 9 becomes

$$d\mathbf{F} = (-P_\infty - \rho_\infty a_\infty [\mathbf{V} \cdot \mathbf{n}]) d\mathbf{A}\mathbf{n}\tag{10}$$

Equation 10 is the basic result upon which this work is based. From this equation, it is seen that in order to compute the forces acting on a surface, one must determine the properties of the flow past the surface (properties behind a shock, expansion fan, or freestream), the velocity of the surface relative to the airstream, \mathbf{V} , the outward pointing surface normal, \mathbf{n} , and the surface element, dA . The work that follows will develop these quantities for the upper and lower surfaces of the vehicle, as well as for the control effectors.

IV. Vehicle Surface Pressure Distributions and Forces

The differential forces on the surfaces of the vehicle were computed by Oppenheimer and Doman⁵ and are repeated below:

$$d\mathbf{F}_{cf} = (-P_{cf} - \rho_{cf}a_{cf} \{[u + q \tan \tau_{1,U} (x - \bar{x}_f)] \sin \tau_{1,U} - [w - qx] \cos \tau_{1,U}\}) \left[\sin \tau_{1,U} \hat{i} - \cos \tau_{1,U} \hat{k} \right] \sec \tau_{1,U} dx\tag{11}$$

$$d\mathbf{F}_{cd} = (-P_{cd} - \rho_{cd}a_{cd} \{[u - q \tan \tau_{1,L} (x - \bar{x}_f)] \sin \tau_{1,L} + [w - qx] \cos \tau_{1,L}\}) \left[\sin \tau_{1,L} \hat{i} + \cos \tau_{1,L} \hat{k} \right] \sec \tau_{1,L} dx\tag{12}$$

$$d\mathbf{F}_{gh} = (-P_{gh} - \rho_{gh}a_{gh} \{w - qx\}) \left[1 \hat{k} \right] dx\tag{13}$$

$$d\mathbf{F}_{ef} = (-P_{ef} - \rho_{ef}a_{ef} \{-(u + qr_{efz}) \sin (\tau_{1,U} + \tau_2) + (w - qx) \cos (\tau_{1,U} + \tau_2)\}) \mathbf{n}_{ef} \sec (\tau_{1,U} + \tau_2) dx\tag{14}$$

where

$$\mathbf{n}_{ef} = -\sin(\tau_{1,U} + \tau_2) \hat{i} + \cos(\tau_{1,U} + \tau_2) \hat{k} \quad (15)$$

and

$$r_{efz} = [\tan(\tau_{1,U} + \tau_2)(x + \bar{x}_a) - L \tan \tau_{1,U}] \quad (16)$$

where u , w , and q are small perturbations in a steady flight condition of the forward velocity, normal velocity, and pitch rate, respectively. The steady forces are computed by integrating the steady components of the differential forces over the corresponding surface. Performing the integrations yields

$$\begin{aligned} \mathbf{F}_{cfa} &= -P_{cf} \bar{x}_a \sec \tau_{1,U} \left[\sin \tau_{1,U} \hat{i} - \cos \tau_{1,U} \hat{k} \right] = X_{cfa} \hat{i} + Z_{cfa} \hat{k} \\ \mathbf{F}_{cfa} &= -P_{cf} \bar{x}_f \sec \tau_{1,U} \left[\sin \tau_{1,U} \hat{i} - \cos \tau_{1,U} \hat{k} \right] = X_{cfa} \hat{i} + Z_{cfa} \hat{k} \end{aligned} \quad (17)$$

where X_{cfa} , Z_{cfa} are the components of the aftbody upper surface force in the x and z directions, respectively, and X_{cfa} , Z_{cfa} are the components of the forebody upper surface force in the x and z directions. The lower surface forces are

$$\begin{aligned} \mathbf{F}_{cd} &= -P_{cd} L_f \sec \tau_{1,L} \left[\sin \tau_{1,L} \hat{i} + \cos \tau_{1,L} \hat{k} \right] = X_{cd} \hat{i} + Z_{cd} \hat{k} \\ \mathbf{F}_{gh} &= -P_{gh} L_n \hat{k} = X_{gh} \hat{i} + Z_{gh} \hat{k} \end{aligned} \quad (18)$$

while on the rear ramp, the vector force due to the external nozzle is

$$\mathbf{F}_{ef} = \frac{L_a P_e P_\infty}{\cos(\tau_{1,U} + \tau_2)(P_e - P_\infty)} \ln \frac{P_e}{P_\infty} \left[\sin(\tau_{1,U} + \tau_2) \hat{i} - \cos(\tau_{1,U} + \tau_2) \hat{k} \right] = X_{ef} \hat{i} + Z_{ef} \hat{k} \quad (19)$$

where X_{ef} and Z_{ef} are the axial and normal force components of the external nozzle force and P_e is the engine exit pressure.

A. Control Surfaces

The control surfaces are an elevator and canard as shown in Fig. 1. Both surfaces are modelled as flat plates hinged at their midpoints so the entire surface deflects. Positive deflection is defined as trailing edge down. The x and z positions of the midpoint of the elevator and canard referenced to the C.G. are x_{elev} , z_{elev} and x_{canard} , 0. The canard was added to this vehicle for two reasons. First, the elevator produces a significant amount of lift and results in a non-minimum phase flight path angle response.⁷ Adding the canard and forcing it to respond in conjunction with the elevator compensates for the lift produced by the elevator and reduces the non-minimum phase behavior. Secondly, the canard can be utilized for low speed control and reduces the takeoff and landing speeds since they produce positive lift in conjunction with a nose up pitching moment. In this work, the canard is not ganged to the elevator, rather, it is free to move. Hence, the non-minimum phase flight path angle response is still present. However, this allows the determination of the steady and unsteady forces and moments due to the canard.

1. Elevator

The upper and lower forces on the elevator can be computed as

$$\mathbf{F}_{eU} = \int_{-x_{elev} - \frac{L_e}{2} \cos \delta_e}^{-x_{elev} + \frac{L_e}{2} \cos \delta_e} [-P_{eU} - \rho_{eU} a_{eU} \{\mathbf{V}_{eU} \cdot \mathbf{n}_{eU}\}] \left[-\sin \delta_e \hat{i} - \cos \delta_e \hat{k} \right] \sec \delta_e dx \quad (20)$$

$$\mathbf{F}_{eL} = \int_{-x_{elev} - \frac{L_e}{2} \cos \delta_e}^{-x_{elev} + \frac{L_e}{2} \cos \delta_e} [-P_{eL} - \rho_{eL} a_{eL} \{\mathbf{V}_{eL} \cdot \mathbf{n}_{eL}\}] \left[\sin \delta_e \hat{i} + \cos \delta_e \hat{k} \right] \sec \delta_e dx \quad (21)$$

where

$$\mathbf{V}_{eU} \cdot \mathbf{n}_{eU} = -(u - q \{z_{elev} + \tan \delta_e (x + x_{elev})\}) \sin \delta_e - (w - qx) \cos \delta_e \quad (22)$$

$$\mathbf{V}_{eL} \cdot \mathbf{n}_{eL} = (u - q \{z_{elev} + \tan \delta_e (x + x_{elev})\}) \sin \delta_e + (w - qx) \cos \delta_e \quad (23)$$

2. Canard

In order to determine the steady and unsteady forces and moments due to the canard, Eq. 10 must be evaluated. Hence, the flow properties on the top and bottom surfaces of the canard along with a position vector, normal vector, and surface element must be determined. For the canard, the flow properties are

$$\begin{aligned} \text{If } \delta_c = -\alpha &\implies \text{Freestream} \\ \text{If } \delta_c < -\alpha &\implies \text{Shock on top, expansion on bottom} \\ \text{If } \delta_c > -\alpha &\implies \text{Expansion on top, shock on bottom} \end{aligned} \quad (24)$$

The position vector from the C.G. to an arbitrary point on the canard is given by

$$\begin{aligned} \mathbf{r}_c &= x\hat{i} + [-\tan\delta_c(x - x_{canard}) + z_{canard}] \\ x_{canard} - \frac{L_c}{2}\cos\delta_c &\leq x \leq x_{canard} + \frac{L_c}{2}\cos\delta_c \end{aligned} \quad (25)$$

where $z_{canard} = 0$ for this configuration. The outward pointing normal vectors for this surface, relative to the body axis, are

$$\begin{aligned} \mathbf{n}_{cU} &= -\sin\delta_c\hat{i} - \cos\delta_c\hat{k} \\ \mathbf{n}_{cL} &= \sin\delta_c\hat{i} + \cos\delta_c\hat{k} \end{aligned} \quad (26)$$

and the surface element is

$$dA_c = \sec\delta_c(1)dx \quad (27)$$

To compute the forces, moments, and stability derivatives, consider small perturbations, from a steady flight condition, in the velocities u and w and the pitch rate q . The velocity of a point on the upper and lower surfaces of the canard, due to these perturbations, is

$$\begin{aligned} \mathbf{V}_{cU} &= (V_{cU}\cos\delta_c + u)\hat{i} + (-V_{cU}\sin\delta_c + w)\hat{k} + \boldsymbol{\omega} \times \mathbf{r}_c \\ \mathbf{V}_{cL} &= (V_{cL}\cos\delta_c + u)\hat{i} + (-V_{cL}\sin\delta_c + w)\hat{k} + \boldsymbol{\omega} \times \mathbf{r}_c \end{aligned} \quad (28)$$

where V_{cU} and V_{cL} are the flow velocities on the upper and lower surface of the canard (as determined from the flow analysis) and $\boldsymbol{\omega} = q\hat{j}$ is the angular rate vector. Using Eqs. 24 - 28 in Eq. 10 yields the differential forces due to the canard:

$$\begin{aligned} d\mathbf{F}_{cU} &= [-P_{cU} - \rho_{cU}a_{cU} \{-\sin\delta_c(u + q[-\tan\delta_c(x - x_{canard}) + z_{canard}]) - \cos\delta_c(w - qz)\}] \mathbf{n}_{cU} dA_{cU} \\ d\mathbf{F}_{cL} &= [-P_{cL} - \rho_{cL}a_{cL} \{\sin\delta_c(u + q[-\tan\delta_c(x - x_{canard}) + z_{canard}]) + \cos\delta_c(w - qz)\}] \mathbf{n}_{cL} dA_{cL} \end{aligned} \quad (29)$$

The steady forces are computed by integrating the steady component of Eq. 29, hence,

$$\begin{aligned} \mathbf{F}_{cU} &= \int_{x_{canard} - \frac{L_c}{2}\cos\delta_c}^{x_{canard} + \frac{L_c}{2}\cos\delta_c} -P_{cU} \left(-\sin\delta_c\hat{i} - \cos\delta_c\hat{k} \right) \sec\delta_c dx = P_{cU}L_c \sin\delta_c\hat{i} + P_{cU}L_c \cos\delta_c\hat{k} = X_{cU}\hat{i} + Z_{cU}\hat{k} \\ \mathbf{F}_{cL} &= \int_{x_{canard} - \frac{L_c}{2}\cos\delta_c}^{x_{canard} + \frac{L_c}{2}\cos\delta_c} -P_{cL} \left(\sin\delta_c\hat{i} + \cos\delta_c\hat{k} \right) \sec\delta_c dx = -P_{cL}L_c \sin\delta_c\hat{i} - P_{cL}L_c \cos\delta_c\hat{k} = X_{cL}\hat{i} + Z_{cL}\hat{k} \end{aligned} \quad (30)$$

The corresponding moments are calculated using $M_{cU} = \mathbf{r}_c \times \mathbf{F}_{cU}$ and $M_{cL} = \mathbf{r}_c \times \mathbf{F}_{cL}$ such that

$$\begin{aligned} M_{cU} &= -x_{canard}P_{cU}L_c \cos\delta_c + z_{canard}P_{cU}L_c \sin\delta_c = -x_{canard}P_{cU}L_c \cos\delta_c \\ M_{cL} &= x_{canard}P_{cL}L_c \cos\delta_c - z_{canard}P_{cL}L_c \sin\delta_c = x_{canard}P_{cL}L_c \cos\delta_c \end{aligned} \quad (31)$$

where the last inequalities in Eq. 31 result from z_{canard} being zero.

V. Unsteady Control Surface Effects

The unsteady effects due to velocity and rate perturbations on the control surfaces are found using the unsteady portions of Eqs. 20, 21, and 29.

A. Elevator Unsteady Effects

The normal force stability derivative due to the elevator is

$$(C_{Z_w})_{\delta_e} = \frac{1}{q_\infty S} \int (d\mathbf{F})_{z-w} = \frac{1}{q_\infty S} \int (d\mathbf{F}_{e_U})_{z-w} + \frac{1}{q_\infty S} \int (d\mathbf{F}_{e_L})_{z-w} \quad (32)$$

Performing the necessary substitutions produces

$$(C_{Z_w})_{\delta_e} = \frac{1}{q_\infty S} \left[\int_{-x_{elev} - \frac{L_e}{2} \cos \delta_e}^{-x_{elev} + \frac{L_e}{2} \cos \delta_e} -\rho_{e_U} a_{e_U} w \cos \delta_e dx + \int_{-x_{elev} - \frac{L_e}{2} \cos \delta_e}^{-x_{elev} + \frac{L_e}{2} \cos \delta_e} -\rho_{e_L} a_{e_L} w \cos \delta_e dx \right] \quad (33)$$

Integrating, letting $w \approx V_\infty \alpha$, and simplifying yields

$$\left(\frac{\partial C_Z}{\partial \alpha} \right)_{\delta_e} = \frac{-(\rho_{e_U} a_{e_U} + \rho_{e_L} a_{e_L}) V_\infty L_e \cos^2 \delta_e}{q_\infty S} \quad (34)$$

Using similar analysis, the axial force component becomes

$$\begin{aligned} (C_{X_w})_{\delta_e} &= \frac{1}{q_\infty S} \int (d\mathbf{F})_{x-w} = \frac{1}{q_\infty S} \int (d\mathbf{F}_{e_U})_{x-w} + \frac{1}{q_\infty S} \int (d\mathbf{F}_{e_L})_{x-w} \\ &\Rightarrow \left(\frac{\partial C_X}{\partial \alpha} \right)_{\delta_e} = \frac{-(\rho_{e_U} a_{e_U} + \rho_{e_L} a_{e_L}) V_\infty L_e \cos \delta_e \sin \delta_e}{q_\infty S} \end{aligned} \quad (35)$$

The pitching moment contribution due to w motion is

$$\begin{aligned} (C_{M_w})_{\delta_e} &= \frac{1}{q_\infty S \bar{c}} \left[\int z (d\mathbf{F}_{e_U})_{x-w} + \int z (d\mathbf{F}_{e_L})_{x-w} - \int x (d\mathbf{F}_{e_U})_{z-w} - \int x (d\mathbf{F}_{e_L})_{z-w} \right] \\ &\Rightarrow \left(\frac{\partial C_M}{\partial \alpha} \right)_{\delta_e} = \frac{(\rho_{e_U} a_{e_U} + \rho_{e_L} a_{e_L}) (z_{elev} L_e \sin \delta_e \cos \delta_e - x_{elev} L_e \cos^2 \delta_e) V_\infty}{q_\infty S \bar{c}} \end{aligned} \quad (36)$$

The normal force increment due to pitch rate is

$$\begin{aligned} (C_{Z_q})_{\delta_e} &= \frac{1}{q_\infty S} \left[\int (d\mathbf{F}_{e_U})_{z-q} + \int (d\mathbf{F}_{e_L})_{z-q} \right] \\ &\Rightarrow \left(\frac{\partial C_Z}{\partial q} \right)_{\delta_e} = \frac{(\rho_{e_U} a_{e_U} + \rho_{e_L} a_{e_L}) [L_e \sin \delta_e \cos \delta_e \{z_{elev} + x_{elev} \tan \delta_e\} - x_{elev} L_e]}{q_\infty S} \end{aligned} \quad (37)$$

The final stability derivative for the elevator is the pitching moment increment due to pitch rate, which becomes

$$(C_{M_q})_{\delta_e} = \frac{1}{q_\infty S \bar{c}} \left[\int z (d\mathbf{F}_{e_U})_{x-q} + \int z (d\mathbf{F}_{e_L})_{x-q} - \int x (d\mathbf{F}_{e_U})_{z-q} - \int x (d\mathbf{F}_{e_L})_{z-q} \right] \quad (38)$$

Performing the required operations yields

$$\begin{aligned} \left(\frac{\partial C_M}{\partial q} \right)_{\delta_e} &= \frac{(\rho_{e_U} a_{e_U} + \rho_{e_L} a_{e_L})}{q_\infty S \bar{c}} [L_e \sin \delta_e \cos \delta_e (\tan \delta_e \{x_{elev}^2 - z_{elev}^2\} + x_{elev} z_{elev} \{1 - \tan^2 \delta_e\})] \\ &\quad + \frac{(\rho_{e_U} a_{e_U} + \rho_{e_L} a_{e_L})}{q_\infty S \bar{c}} (z_{elev} + x_{elev} \tan \delta_e) x_{elev} L_e \tan \delta_e \\ &\quad - \frac{(\rho_{e_U} a_{e_U} + \rho_{e_L} a_{e_L})}{q_\infty S \bar{c}} \left(\frac{\tan^2 \delta_e - 1}{3 \cos \delta_e} \right) \left(\left\{ -x_{elev} + \frac{L_e}{2} \cos \delta_e \right\}^3 - \left\{ -x_{elev} - \frac{L_e}{2} \cos \delta_e \right\}^3 \right) \end{aligned} \quad (39)$$

B. Canard Unsteady Effects

The normal force stability derivative due to the canard is

$$(C_{Z_w})_{\delta_c} = \frac{1}{q_\infty S} \int (d\mathbf{F}_{c_U})_{z-w} + \frac{1}{q_\infty S} \int (d\mathbf{F}_{c_L})_{z-w} \quad (40)$$

which becomes

$$\left(\frac{\partial C_Z}{\partial \alpha}\right)_{\delta_c} = -\frac{(\rho_{c_U} a_{c_U} + \rho_{c_L} a_{c_L}) (V_\infty L_c \cos^2 \delta_c)}{q_\infty S} \quad (41)$$

The axial force increment due to motion in the vertical direction becomes

$$\begin{aligned} (C_{X_w})_{\delta_c} &= \frac{1}{q_\infty S} \int (d\mathbf{F}_{C_U})_{x-w} + \frac{1}{q_\infty S} \int (d\mathbf{F}_{C_L})_{x-w} \\ \Rightarrow \left(\frac{\partial C_X}{\partial \alpha}\right)_{\delta_c} &= \frac{-(\rho_{c_U} a_{c_U} + \rho_{c_L} a_{c_L}) V_\infty L_c \cos \delta_c \sin \delta_c}{q_\infty S} \end{aligned} \quad (42)$$

The pitching moment contribution due to w motion is

$$\begin{aligned} (C_{M_w})_{\delta_c} &= \frac{1}{q_\infty S \bar{c}} \left[\int z (d\mathbf{F}_{C_U})_{x-w} + \int z (d\mathbf{F}_{C_L})_{x-w} - \int x (d\mathbf{F}_{C_U})_{z-w} - \int x (d\mathbf{F}_{C_L})_{z-w} \right] \\ \Rightarrow \left(\frac{\partial C_M}{\partial \alpha}\right)_{\delta_c} &= \frac{(\rho_{c_U} a_{c_U} + \rho_{c_L} a_{c_L}) (-z_{canard} L_c \sin \delta_c \cos \delta_c + x_{canard} L_c \cos^2 \delta_c) V_\infty}{q_\infty S \bar{c}} \end{aligned} \quad (43)$$

The normal force increment due to pitch rate is

$$\begin{aligned} (C_{Z_q})_{\delta_c} &= \frac{1}{q_\infty S} \left[\int (d\mathbf{F}_{C_U})_{z-q} + \int (d\mathbf{F}_{C_L})_{z-q} \right] \\ \Rightarrow \left(\frac{\partial C_Z}{\partial q}\right)_{\delta_c} &= \frac{(\rho_{c_U} a_{c_U} + \rho_{c_L} a_{c_L}) [x_{canard} L_c \cos^2 \delta_c - z_{canard} L_c \sin \delta_c \cos \delta_c]}{q_\infty S} \end{aligned} \quad (44)$$

The final stability derivative for the canard is the pitching moment increment due to pitch rate, which becomes

$$(C_{M_q})_{\delta_c} = \frac{1}{q_\infty S \bar{c}} \left[\int z (d\mathbf{F}_{C_U})_{x-q} + \int z (d\mathbf{F}_{C_L})_{x-q} - \int x (d\mathbf{F}_{C_U})_{z-q} - \int x (d\mathbf{F}_{C_L})_{z-q} \right] \quad (45)$$

Performing the required operations yields

$$\left(\frac{\partial C_M}{\partial q}\right)_{\delta_c} = \frac{(\rho_{c_U} a_{c_U} + \rho_{c_L} a_{c_L})}{q_\infty S \bar{c}} \left[-\frac{\sin^2 \delta_c L_c^3}{12} - z_{canard}^2 L_c \sin^2 \delta_c - \frac{L_c^3}{12} \sin^2 \delta_c \cos^2 \delta_c - x_{canard}^2 L_c \cos^2 \delta_c - \frac{L_c^3 \cos^4 \delta_c}{12} \right] \quad (46)$$

VI. Total Forces and Moments - Rigid Body

With the inclusion of the stability derivatives, the thrust, and resulting engine moment,⁵ the total aerodynamic forces and moments on the vehicle are

$$\begin{aligned} X_{total} &= X_{c_{f_f}} + X_{c_{f_a}} + X_{cd} + X_{gh} + X_{ef} + X_{e_L} + X_{e_U} + X_{c_U} + X_{c_L} + T + q_\infty S \frac{\partial C_X}{\partial \alpha} \alpha \\ &\quad + q_\infty S \left(\frac{\partial C_X}{\partial \alpha}\right)_{\delta_e} \alpha + q_\infty S \left(\frac{\partial C_X}{\partial \alpha}\right)_{\delta_c} \alpha \end{aligned} \quad (47)$$

$$\begin{aligned} Z_{total} &= Z_{c_{f_f}} + Z_{c_{f_a}} + Z_{cd} + Z_{gh} + Z_{ef} + Z_{e_L} + Z_{e_U} + Z_{c_U} + Z_{c_L} + q_\infty S \frac{\partial C_Z}{\partial \alpha} \alpha + q_\infty S \frac{\partial C_Z}{\partial q} \frac{q \bar{c}}{2V_\infty} \\ &\quad + q_\infty S \left(\frac{\partial C_Z}{\partial \alpha}\right)_{\delta_e} \alpha + q_\infty S \left(\frac{\partial C_Z}{\partial \alpha}\right)_{\delta_c} \alpha + q_\infty S \left(\frac{\partial C_Z}{\partial q}\right)_{\delta_e} \frac{q \bar{c}}{2V_\infty} + q_\infty S \left(\frac{\partial C_Z}{\partial q}\right)_{\delta_c} \frac{q \bar{c}}{2V_\infty} \end{aligned} \quad (48)$$

$$\begin{aligned} M_{total} &= M_{c_{f_f}} + M_{c_{f_a}} + M_{cd} + M_{gh} + M_{ef} + M_{e_L} + M_{e_U} + M_{c_U} + M_{c_L} + M_{engine} + q_\infty S \bar{c} \frac{\partial C_M}{\partial \alpha} \alpha + \\ &\quad q_\infty S \bar{c} \frac{\partial C_M}{\partial q} \frac{q \bar{c}}{2V_\infty} + q_\infty S \bar{c} \left(\frac{\partial C_M}{\partial \alpha}\right)_{\delta_e} \alpha + q_\infty S \bar{c} \left(\frac{\partial C_M}{\partial \alpha}\right)_{\delta_c} \alpha + q_\infty S \bar{c} \left(\frac{\partial C_M}{\partial q}\right)_{\delta_e} \frac{q \bar{c}}{2V_\infty} + q_\infty S \bar{c} \left(\frac{\partial C_M}{\partial q}\right)_{\delta_c} \frac{q \bar{c}}{2V_\infty} \end{aligned} \quad (49)$$

where M_{engine} and T are the moment and thrust produced by the engine. It can be seen that Eqs. 47- 49 do not contain any inlet turning forces/moments that was present in previous work. Here, a reflected shock from the engine inlet was modelled and performs the flow turning.

VII. Flexible Effects

Thus far, only unsteady effects due to rigid body motion have been considered. Full scale hypersonic airbreathing vehicles are expected to be long and slender and thus highly flexible. This structural bending affects downstream flow resulting in localized changes in surface pressure along the body and thus, should be incorporated into the model. In this section, the flexible effects are included in the analysis. Piston theory is still used to determine the pressure distribution on the surfaces of the vehicle and much of the analysis already presented can be easily adapted to included these additional effects.

A. Flexible Model

In order to develop the aeroelastic model, a few assumptions are made. First, the flexible vehicle is modelled as two cantilever beams fixed at the c.g. (one for the forebody section of the vehicle and one for the aftbody section of the vehicle). Second, the beams are assumed to have constant mass density, area, and flexural rigidity (EI), where EI is chosen to give the desired natural frequency of vibration. Also, it is assumed that the flexible effects only perturb the surface velocities in the z (normal) direction. This assumption is justified using the small angle approximation, i.e., the deflection of the tip of the beam is small compared to the length of the beam. Lastly, it is assumed that the change in angle of attack, as seen by the entire forebody, is the change in angle of attack as seen by the tip of the vehicle, point $(\bar{x}_f, 0)$ in Fig. 1. Since the tip experiences the largest deflection, this is a worst-case assumption. This change in angle of attack is used to compute the flow properties behind the bow shock and those flow properties are assumed constant over the lower forebody.

The transverse vibrations in the beam satisfy the following partial differential equation:⁸

$$EI \frac{\partial^4 w(x, t)}{\partial x^4} + \hat{m} \frac{\partial^2 w(x, t)}{\partial t^2} = 0 \quad (50)$$

where $w(x, t)$ describes the position of the beam, relative to the body x -axis, E is Young's Modulus, I is the moment of inertia of the beam cross-section about the y -axis, and \hat{m} is the mass density of the beam. This problem is typically solved using separation of variables. Assume

$$w(x, t) = \Phi(x)\eta(t) \quad (51)$$

Substituting the expression for $w(x, t)$ in Eq. 51 into Eq. 50 and simplifying yields

$$\frac{EI}{\hat{m}\Phi(x)} \frac{\partial^4 \Phi(x)}{\partial x^4} = -\frac{1}{\eta(t)} \frac{\partial^2 \eta(t)}{\partial t^2} \quad (52)$$

Since the left side of Eq. 52 does not change as time varies, the right side of Eq. 52 must be a constant. Similarly, since the right side of Eq. 52 does not change as x varies, the left side of Eq. 52 must be a constant. Let this constant be ω^2 , such that

$$\frac{EI}{\hat{m}\Phi(x)} \frac{\partial^4 \Phi(x)}{\partial x^4} = -\frac{1}{\eta(t)} \frac{\partial^2 \eta(t)}{\partial t^2} = \omega^2 \quad (53)$$

Utilizing the method of separation of variables, Eq. 53 can be written as two differential equations, one with respect to position and one with respect to time:

$$\frac{\partial^4 \Phi(x)}{\partial x^4} - \beta^4 \Phi(x) = 0 \quad (54)$$

$$\frac{\partial^2 \eta(t)}{\partial t^2} + \omega^2 \eta(t) = 0 \quad (55)$$

where $\beta^4 = \frac{\omega^2 \hat{m}}{EI}$. The general solution to Eq. 54 is⁸

$$\Phi(x) = C_1 \sin \beta x + C_2 \cos \beta x + C_3 \sinh \beta x + C_4 \cosh \beta x \quad (56)$$

Using the following boundary conditions for the forward beam

$$\begin{aligned} \frac{d^2 \Phi(x)}{dx^2} \Big|_{x=\bar{x}_f} &= 0 & \frac{d^3 \Phi(x)}{dx^3} \Big|_{x=\bar{x}_f} &= 0 \\ \Phi(x) \Big|_{x=0} &= 0 & \frac{d\Phi(x)}{dx} \Big|_{x=0} &= 0 \end{aligned} \quad (57)$$

which state that the bending moment and shear force are zero at the free location ($x = \bar{x}_f$) and the displacement and slope are zero at the fixed location ($x = 0$), along with the modal shape expression, (Eq. 56), and simplifying results in the frequency equation

$$\cos \beta_f \bar{x}_f \cosh \beta_f \bar{x}_f = -1 \quad (58)$$

Eq. 58 has an infinite number of solutions with the first few given by

$$\beta_{f,r} \bar{x}_f = 1.8751, 4.6941, 7.8548, 10.9955, 14.1372, \dots \quad (59)$$

The values of $\beta_{f,r}$, $r = 1, 2, 3, \dots$ in Eq. 59 are called the eigenvalues. Corresponding to these eigenvalues, the natural modes of the forward beam are⁸

$$\begin{aligned} \Phi_{f,r}(x) = & A_{f,r} [(\sin \beta_{f,r} \bar{x}_f - \sinh \beta_{f,r} \bar{x}_f) (\sin \beta_{f,r} x - \sinh \beta_{f,r} x)] \\ & + A_{f,r} [(\cos \beta_{f,r} \bar{x}_f + \cosh \beta_{f,r} \bar{x}_f) (\cos \beta_{f,r} x - \cosh \beta_{f,r} x)] \end{aligned} \quad (60)$$

where $A_{f,r}$ is a normalizing factor, selected such that

$$\int_0^{\bar{x}_f} \hat{m}_f \Phi_{f,r}^2(x) dx = 1 \quad (61)$$

where \hat{m}_f is the mass density of the forebody beam defined as

$$\hat{m}_f = \frac{Mass \left(1 - \frac{\bar{x}_f}{L}\right)}{\bar{x}_f} \quad (62)$$

Thus, $A_{f,r}$ becomes

$$A_{f,r} = \frac{1}{\sqrt{\hat{m}_f [A_{f,r_{P_1}} + A_{f,r_{P_2}} + A_{f,r_{P_3}}]}} \quad (63)$$

where

$$A_{f,r_{P_1}} = \frac{(\sin \beta_{f,r} \bar{x}_f - \sinh \beta_{f,r} \bar{x}_f)^2}{4\beta_{f,r}} [M_{1f}] \quad (64)$$

$$A_{f,r_{P_2}} = \frac{(\sin \beta_{f,r} \bar{x}_f - \sinh \beta_{f,r} \bar{x}_f) (\cos \beta_{f,r} \bar{x}_f + \cosh \beta_{f,r} \bar{x}_f)}{\beta_{f,r}} (\sin \beta_{f,r} \bar{x}_f - \sinh \beta_{f,r} \bar{x}_f)^2 \quad (65)$$

$$A_{f,r_{P_3}} = \frac{(\cos \beta_{f,r} \bar{x}_f + \cosh \beta_{f,r} \bar{x}_f)^2}{4\beta_{f,r}} [M_{3f}] \quad (66)$$

and

$$M_{1f} = -2 \cos \beta_{f,r} \bar{x}_k \sin \beta_{f,r} \bar{x}_k + \sinh 2\beta_{f,r} \bar{x}_k - 4 \sin \beta_{f,r} \bar{x}_k \cosh \beta_{f,r} \bar{x}_k + 4 \cos \beta_{f,r} \bar{x}_k \sinh \beta_{f,r} \bar{x}_k \quad (67)$$

$$M_{3f} = 2 \cos \beta_{f,r} \bar{x}_k \sin \beta_{f,r} \bar{x}_k + \sinh 2\beta_{f,r} \bar{x}_k - 4 \cos \beta_{f,r} \bar{x}_k \sinh \beta_{f,r} \bar{x}_k - 4 \sin \beta_{f,r} \bar{x}_k \cosh \beta_{f,r} \bar{x}_k + 4\beta_{f,r} \bar{x}_k \quad (68)$$

For the aft beam, the boundary conditions are

$$\begin{aligned} \frac{d^2 \Phi(x)}{dx^2} \Big|_{x=\bar{x}_a} &= 0 & \frac{d^3 \Phi(x)}{dx^3} \Big|_{x=\bar{x}_a} &= 0 \\ \Phi(x) \Big|_{x=0} &= 0 & \frac{d\Phi(x)}{dx} \Big|_{x=0} &= 0 \end{aligned} \quad (69)$$

and the frequency equation becomes

$$\cos \beta_a \bar{x}_a \cosh \beta_a \bar{x}_a = -1 \quad (70)$$

with solutions

$$\beta_{a,r} \bar{x}_a = 1.8751, 4.6941, 7.8548, 10.9955, 14.1372, \dots \quad (71)$$

The natural modes of the aft beam are

$$\begin{aligned} \Phi_{a,r}(x) = & A_{a,r} [(\sin \beta_{a,r} \bar{x}_a - \sinh \beta_{a,r} \bar{x}_a) (\sin \beta_{a,r} x - \sinh \beta_{a,r} x)] \\ & + A_{a,r} [(\cos \beta_{a,r} \bar{x}_a + \cosh \beta_{a,r} \bar{x}_a) (\cos \beta_{a,r} x - \cosh \beta_{a,r} x)] \end{aligned} \quad (72)$$

and $A_{a,r}$ is selected such that

$$\int_0^{\bar{x}_a} \hat{m}_a \Phi_{a,r}^2(x) dx = 1 \quad (73)$$

and

$$\hat{m}_a = \frac{Mass \left(1 - \frac{\bar{x}_a}{L}\right)}{\bar{x}_a} \quad (74)$$

Thus, $A_{a,r}$ becomes

$$A_{a,r} = \frac{1}{\sqrt{\hat{m}_a \left[A_{a,r_{P_1}} + A_{a,r_{P_2}} + A_{a,r_{P_3}} \right]}} \quad (75)$$

where

$$A_{a,r_{P_1}} = \frac{(\sin \beta_{a,r} \bar{x}_a - \sinh \beta_{a,r} \bar{a}_f)^2}{4\beta_{a,r}} [M_{1a}] \quad (76)$$

$$A_{a,r_{P_2}} = \frac{(\sin \beta_{a,r} \bar{x}_a - \sinh \beta_{a,r} \bar{x}_a) (\cos \beta_{a,r} \bar{x}_a + \cosh \beta_{a,r} \bar{x}_a)}{\beta_{a,r}} (\sin \beta_{a,r} \bar{x}_a - \sinh \beta_{a,r} \bar{x}_a)^2 \quad (77)$$

$$A_{a,r_{P_3}} = \frac{(\cos \beta_{a,r} \bar{x}_a + \cosh \beta_{a,r} \bar{x}_a)^2}{4\beta_{a,r}} [M_{3a}] \quad (78)$$

and

$$M_{1a} = -2 \cos \beta_{a,r} \bar{x}_a \sin \beta_{a,r} \bar{x}_a + \sinh 2\beta_{a,r} \bar{x}_a - 4 \sin \beta_{a,r} \bar{x}_a \cosh \beta_{a,r} \bar{x}_a + 4 \cos \beta_{a,r} \bar{x}_a \sinh \beta_{a,r} \bar{x}_a \quad (79)$$

$$M_{3a} = 2 \cos \beta_{a,r} \bar{x}_a \sin \beta_{a,r} \bar{x}_a + \sinh 2\beta_{a,r} \bar{x}_a - 4 \cos \beta_{a,r} \bar{x}_a \sinh \beta_{a,r} \bar{x}_a - 4 \sin \beta_{a,r} \bar{x}_a \cosh \beta_{a,r} \bar{x}_a + 4 \beta_{a,r} \bar{x}_a \quad (80)$$

B. Forced Response

Let the forcing function in Eq. 50 consist of distributed and concentrated loads so that Eq. 50 can be written as

$$EI \frac{\partial^4 w(x,t)}{\partial x^4} + \hat{m} \frac{\partial^2 w(x,t)}{\partial t^2} = f(x,t) + F_j(t) \delta(x - x_j) \quad (81)$$

where $\delta(x)$ is the dirac delta function defined as

$$\delta(x - x_j) = \begin{cases} 1 & \text{if } x = x_j \\ 0 & \text{if } x \neq x_j \end{cases} \quad (82)$$

From the expansion theorem, the solution to Eq. 81 is

$$w_f(x,t) = \sum_{r=1}^{\infty} \Phi_{f,r}(x) \eta_{f,r}(t) \quad (83)$$

for the forebody beam and

$$w_a(x,t) = \sum_{r=1}^{\infty} \Phi_{a,r}(x) \eta_{a,r}(t) \quad (84)$$

for the aftbody beam where $\eta_{f,r}(t)$, $\eta_{a,r}(t)$ are the generalized modal coordinates, for the forebody and aftbody beams, that satisfy

$$\begin{aligned} \ddot{\eta}_{f,r}(t) + 2\zeta_{f,r} \omega_{f,r} \dot{\eta}_{f,r}(t) + \omega_{f,r}^2 \eta_{f,r}(t) &= N_{f,r}(t) \\ \ddot{\eta}_{a,r}(t) + 2\zeta_{a,r} \omega_{a,r} \dot{\eta}_{a,r}(t) + \omega_{a,r}^2 \eta_{a,r}(t) &= N_{a,r}(t) \end{aligned} \quad (85)$$

Here, $N_{f,r}(t)$, $N_{a,r}(t)$ are generalized forces for the r^{th} mode shape of the forebody/aftbody beam, defined by⁸

$$\begin{aligned} N_{f,r}(t) &= \int_0^{\bar{x}_f} \Phi_{f,r}(x) f_f(x,t) dx + \sum_{j=1}^n \Phi_{f,r}(x_j) F_{f,j}(t) \\ N_{a,r}(t) &= \int_0^{\bar{x}_a} \Phi_{a,r}(x) f_a(x,t) dx + \sum_{j=1}^n \Phi_{a,r}(x_j) F_{a,j}(t) \end{aligned} \quad (86)$$

where n is the number of concentrated loads on the beam. Given the loading on the forebody and aftbody beams, the generalized forces for the first mode become

$$\begin{aligned} N_{f,1}(t) &= \int_0^{\bar{x}_f} \Phi_{f,1}(x) P_{cf} dx - \int_{\bar{x}_f-L_f}^{\bar{x}_f} \Phi_{f,1}(x) P_{cd} dx + \Phi_{f,1}(x_{canard}) (P_{cu} - P_{cl}) L_c \\ N_{a,1}(t) &= \int_0^{\bar{x}_a} \Phi_{a,1}(x) P_{cf} dx - \int_{\bar{x}_a-L_a}^{\bar{x}_a} \Phi_{a,1}(x) P_{ef} dx + \Phi_{a,1}(x_{elev}) (P_{eu} - P_{el}) L_e \end{aligned} \quad (87)$$

These expressions are displayed in Appendix A.

In order to incorporate aeroelastic effects into the model, a few simplifying assumptions are made. First, the vehicle does not stretch or compress along the x -axis. Second, for small displacements, when the beams (vehicle) flexes, there is no change in the x direction displacement. With these assumptions, aeroelastic effects only occur in the z -direction. Additionally, it is assumed that the engine nacelle is rigid. The aeroelastic effects can be accounted for by taking the time derivative of Eqs. 83 and 84

$$\begin{aligned} \dot{w}_f(x, t) &= \sum_{r=1}^{\infty} \Phi_{f,r}(x) \dot{\eta}_{f,r}(t) \\ \dot{w}_a(x, t) &= \sum_{r=1}^{\infty} \Phi_{a,r}(x) \dot{\eta}_{a,r}(t) \end{aligned} \quad (88)$$

and including this effect in the expressions for the velocities on the upper and lower surfaces, namely Eqs. 11, 12, and 14. The differential forces on the surfaces become

$$d\mathbf{F}_{cf_f} = (-P_{cf} - \rho_{cf} a_{cf} \{ [u + q \tan \tau_{1,U} (x - \bar{x}_f)] \sin \tau_{1,U} - [w - qx + \dot{w}_f(x, t)] \cos \tau_{1,U} \}) \sec \tau_{1,U} \mathbf{n}_{cf} dx \quad (89)$$

$$d\mathbf{F}_{cf_a} = (-P_{cf} - \rho_{cf} a_{cf} \{ [u + q \tan \tau_{1,U} (x - \bar{x}_f)] \sin \tau_{1,U} - [w - qx + \dot{w}_a(x, t)] \cos \tau_{1,U} \}) \sec \tau_{1,U} \mathbf{n}_{cf} dx \quad (90)$$

$$d\mathbf{F}_{cd} = (-P_{cd} - \rho_{cd} a_{cd} \{ [u - q \tan \tau_{1,L} (x - \bar{x}_f)] \sin \tau_{1,L} + [w - qx + \dot{w}_f(x, t)] \cos \tau_{1,L} \}) \sec \tau_{1,L} \mathbf{n}_{cd} dx \quad (91)$$

$$d\mathbf{F}_{ef} = (-P_{ef} - \rho_{ef} a_{ef} \{ -(u + q r_{efz}) \sin (\tau_{1,U} + \tau_2) + (w - qx + \dot{w}_a(x, t)) \cos (\tau_{1,U} + \tau_2) \}) \sec (\tau_{1,U} + \tau_2) \mathbf{n}_{ef} dx \quad (92)$$

where the upper surface force has been split into forebody and aftbody parts to account for the two beam structural model. With these differential forces, stability derivatives due to the bending of the vehicle can be determined. For the normal force on the forebody beam,

$$\begin{aligned} (C_Z)_{\dot{w}_{forebody}} &= \frac{1}{q_{\infty} S} \left[\int_0^{\bar{x}_f} (d\mathbf{F}_{cf})_{z-\dot{w}} + \int_{\bar{x}_f-L_f}^{\bar{x}_f} (d\mathbf{F}_{cd})_{z-\dot{w}} \right] \\ &= \frac{1}{q_{\infty} S} \int_0^{\bar{x}_f} -\rho_{cf} a_{cf} \dot{w} \cos \tau_{1,U} dx + \int_{\bar{x}_f-L_f}^{\bar{x}_f} -\rho_{cd} a_{cd} \dot{w} \cos \tau_{1,L} dx \end{aligned} \quad (93)$$

Substituting Eq. 88 into Eq. 93 produces

$$(C_Z)_{\dot{w}_{forebody}} = \frac{1}{q_{\infty} S} \int_0^{\bar{x}_f} -\rho_{cf} a_{cf} \sum_{r=1}^{\infty} \Phi_{f,r}(x) \dot{\eta}_{f,r}(t) \cos \tau_{1,U} dx + \int_{\bar{x}_f-L_f}^{\bar{x}_f} -\rho_{cd} a_{cd} \sum_{r=1}^{\infty} \Phi_{f,r}(x) \dot{\eta}_{f,r}(t) \cos \tau_{1,L} dx \quad (94)$$

which, for the first bending mode becomes

$$\begin{aligned} \frac{\partial C_Z}{\partial \dot{\eta}_{f,1}} &= \frac{1}{q_{\infty} S} \int_0^{\bar{x}_f} -\rho_{cf} a_{cf} \Phi_{f,1}(x) \cos \tau_{1,U} dx + \int_{\bar{x}_f-L_f}^{\bar{x}_f} -\rho_{cd} a_{cd} \Phi_{f,1}(x) \cos \tau_{1,L} dx \\ &= \frac{1}{q_{\infty} S} \left[\frac{-2\rho_{cf} a_{cf} \cos \tau_{1,U} A_{f,1}}{\beta_{f,1}} (\sin \beta_{f,1} \bar{x}_f - \sinh \beta_{f,1} \bar{x}_f) \right] \\ &\quad - \frac{\rho_{cd} a_{cd} \cos \tau_{1,L} A_{f,1}}{\beta_{f,1} q_{\infty} S} [(\sin \beta_{f,1} \bar{x}_f - \sinh \beta_{f,1} \bar{x}_f) (\cos \beta_{f,1} (\bar{x}_f - L_f) + \cosh \beta_{f,1} (\bar{x}_f - L_f))] \\ &\quad - \frac{\rho_{cd} a_{cd} \cos \tau_{1,L} A_{f,1}}{\beta_{f,1} q_{\infty} S} [(\cos \beta_{f,1} \bar{x}_f + \cosh \beta_{f,1} \bar{x}_f) (-\sin \beta_{f,1} (\bar{x}_f - L_f) + \sinh \beta_{f,1} (\bar{x}_f - L_f))] \end{aligned} \quad (95)$$

where $A_{f,1}$ is the normalizing factor associated with the first mode. Using the assumption that the flexible effects only perturb the surface velocities in the z-direction, the axial force stability derivative associated with the flexible effect becomes

$$\frac{\partial C_X}{\partial \dot{\eta}_{f,1} \text{ forebody}} = 0 \quad (96)$$

For the pitching moment,

$$(C_M)_{\dot{w}_{forebody}} = \frac{1}{q_\infty S \bar{c}} \left[\int_0^{\bar{x}_f} z (d\mathbf{F}_{cf})_{x-\dot{w}} + \int_{\bar{x}_f-L_f}^{\bar{x}_f} z (d\mathbf{F}_{cd})_{x-\dot{w}} \right] - \frac{1}{q_\infty S \bar{c}} \left[\int_0^{\bar{x}_f} x (d\mathbf{F}_{cf})_{z-\dot{w}} + \int_{\bar{x}_f-L_f}^{\bar{x}_f} x (d\mathbf{F}_{cd})_{z-\dot{w}} \right] \quad (97)$$

For the first mode only, this expression is displayed in Appendix A.

For the aftbody beam, the Z direction force due to flexibility is

$$(C_Z)_{\dot{w}_{aftbody}} = \frac{1}{q_\infty S} \left[\int_0^{\bar{x}_a} (d\mathbf{F}_{cf})_{z-\dot{w}} + \int_{\bar{x}_a-L_a}^{\bar{x}_a} (d\mathbf{F}_{ef})_{z-\dot{w}} \right] \quad (98)$$

and this expression is evaluated in Appendix A.

The pitching moment coefficient due to aftbody flexibility is

$$(C_M)_{\dot{w}_{aftbody}} = \frac{1}{q_\infty S \bar{c}} \left[\int_0^{\bar{x}_a} z (d\mathbf{F}_{cf})_{x-\dot{w}} + \int_{\bar{x}_a-L_a}^{\bar{x}_a} z (d\mathbf{F}_{ef})_{x-\dot{w}} \right] - \frac{1}{q_\infty S \bar{c}} \left[\int_0^{\bar{x}_a} x (d\mathbf{F}_{cf})_{z-\dot{w}} + \int_{\bar{x}_a-L_a}^{\bar{x}_a} x (d\mathbf{F}_{ef})_{z-\dot{w}} \right] \quad (99)$$

and this expression is evaluated in Appendix A for the first bending mode.

With the inclusion of the flexible stability derivatives, the total aerodynamic forces and moments on the vehicle are

$$X_{total} = X_{cff} + X_{cfa} + X_{cd} + X_{gh} + X_{ef} + X_{eL} + X_{eU} + X_{cU} + X_{cL} + T + q_\infty S \frac{\partial C_X}{\partial \alpha} \alpha + q_\infty S \left(\frac{\partial C_X}{\partial \alpha} \right)_{\delta_e} \alpha + q_\infty S \left(\frac{\partial C_X}{\partial \alpha} \right)_{\delta_c} \alpha \quad (100)$$

$$Z_{total} = Z_{cff} + Z_{cfa} + Z_{cd} + Z_{gh} + Z_{ef} + Z_{eL} + Z_{eU} + Z_{cU} + Z_{cL} + q_\infty S \frac{\partial C_Z}{\partial \alpha} \alpha + q_\infty S \frac{\partial C_Z}{\partial q} \frac{q\bar{c}}{2V_\infty} + q_\infty S \left(\frac{\partial C_Z}{\partial \alpha} \right)_{\delta_e} \alpha + q_\infty S \left(\frac{\partial C_Z}{\partial \alpha} \right)_{\delta_c} \alpha + q_\infty S \left(\frac{\partial C_Z}{\partial q} \right)_{\delta_e} \frac{q\bar{c}}{2V_\infty} + q_\infty S \left(\frac{\partial C_Z}{\partial q} \right)_{\delta_c} \frac{q\bar{c}}{2V_\infty} + q_\infty S \frac{\partial C_Z}{\partial \dot{\eta}_{a,1}} + q_\infty S \frac{\partial C_Z}{\partial \dot{\eta}_{f,1}} \quad (101)$$

$$M_{total} = M_{cff} + M_{cfa} + M_{cd} + M_{gh} + M_{ef} + M_{eL} + M_{eU} + M_{cU} + M_{cL} + M_{engine} + q_\infty S \bar{c} \frac{\partial C_M}{\partial \alpha} \alpha + q_\infty S \bar{c} \frac{\partial C_M}{\partial q} \frac{q\bar{c}}{2V_\infty} + q_\infty S \bar{c} \left(\frac{\partial C_M}{\partial \alpha} \right)_{\delta_e} \alpha + q_\infty S \bar{c} \left(\frac{\partial C_M}{\partial \alpha} \right)_{\delta_c} \alpha + q_\infty S \bar{c} \left(\frac{\partial C_M}{\partial q} \right)_{\delta_e} \frac{q\bar{c}}{2V_\infty} + q_\infty S \bar{c} \left(\frac{\partial C_M}{\partial q} \right)_{\delta_c} \frac{q\bar{c}}{2V_\infty} + q_\infty S \bar{c} \frac{\partial C_M}{\partial \dot{\eta}_{a,1}} \dot{\eta}_{a,1} + q_\infty S \bar{c} \frac{\partial C_M}{\partial \dot{\eta}_{f,1}} \dot{\eta}_{f,1} \quad (102)$$

C. Equations of Motion for a Flexible Vehicle

The equations of motion for the flexible vehicle are⁶

$$\begin{aligned}
\dot{V}_T &= \frac{1}{m} (T \cos \alpha - D) - g \sin (\theta - \alpha) \\
\dot{\alpha} &= \frac{1}{m V_T} (-T \sin \alpha - L) + Q + \frac{g}{V_T} \cos (\theta - \alpha) \\
I_{yy} \dot{Q} - \Psi_f \ddot{\eta}_f - \Psi_a \ddot{\eta}_a &= M \\
\dot{\theta} &= Q \\
k_f \ddot{\eta}_f + 2\zeta_f \omega_f \dot{\eta}_f + \omega_f^2 \eta_f &= N_f - \Psi_f \frac{M}{I_{yy}} - \frac{\Psi_f \Psi_a \ddot{\eta}_a}{J_{yy}} \\
k_a \ddot{\eta}_a + 2\zeta_a \omega_a \dot{\eta}_a + \omega_a^2 \eta_a &= N_a - \Psi_a \frac{M}{I_{yy}} - \frac{\Psi_f \Psi_a \ddot{\eta}_f}{J_{yy}} \\
\dot{h} &= V_T \sin (\theta - \alpha)
\end{aligned} \tag{103}$$

where

$$\begin{aligned}
\Psi_f &= \int_0^{\bar{x}_f} x \Phi_{f,1}(x) dx \\
k_f &= 1 + \frac{\Psi_f}{I_{yy}} \\
\Psi_a &= \int_0^{\bar{x}_a} x \Phi_{a,1}(x) dx \\
k_a &= 1 + \frac{\Psi_a}{I_{yy}}
\end{aligned} \tag{104}$$

Clearly, the flexible effects are coupled into the pitch rate equation. In addition to this, the bending of the structure has an effect on the angle of attack of the vehicle. Since engine performance is a function of shock angle and shock angle is a function of angle of attack, a significant change to the vehicle's performance can occur due to structural bending. It is assumed, from the point of view of the bow shock, that the entire forebody observes the same change in angle of attack as seen at the nose of the vehicle. In other words, the worst case change in angle of attack is used for the entire forebody. This change in angle of attack is computed as:

$$\Delta\alpha = \arctan [\Phi'_f(\bar{x}_f) \eta_{f,1}(t)] \tag{105}$$

The control surfaces also see a change in angle of attack, which affects the properties of the flow over the surfaces. These changes are given by

$$\Delta\alpha_{canard} = \arctan [\Phi'_f(x_{canard}) \eta_{f,1}(t)] \tag{106}$$

$$\Delta\alpha_{cs} = \arctan [\Phi'_a(x_{elev}) \eta_{a,1}(t)] \tag{107}$$

so that the total angle of attack seen by the control surfaces is

$$\begin{aligned}
\alpha_{canard} &= \alpha + \Delta\alpha_{canard} \\
\alpha_{elev} &= \alpha + \Delta\alpha_{elev}
\end{aligned} \tag{108}$$

The forces due to the control effectors, as given in Eqs. 20, 21 and 30 are written in the rigid vehicle's body axis frame. However, when the structure bends, these forces are not aligned with the body axis and therefore, must be rotated back into the body axis frame. This is accomplished using

$$\begin{aligned}
\mathbf{F}_{eU} &= P_{eU} L_e \sin(\delta_e + \Delta\alpha_e) \hat{i} + P_{eU} L_e \cos(\delta_e + \Delta\alpha_e) \hat{k} \\
\mathbf{F}_{eL} &= -P_{eL} L_e \sin(\delta_e + \Delta\alpha_e) \hat{i} - P_{eL} L_e \cos(\delta_e + \Delta\alpha_e) \hat{k}
\end{aligned} \tag{109}$$

and

$$\begin{aligned}
\mathbf{F}_{cU} &= P_{cU} L_c \sin(\delta_c + \Delta\alpha_c) \hat{i} + P_{cU} L_c \cos(\delta_c + \Delta\alpha_c) \hat{k} \\
\mathbf{F}_{cL} &= -P_{cL} L_c \sin(\delta_c + \Delta\alpha_c) \hat{i} - P_{cL} L_c \cos(\delta_c + \Delta\alpha_c) \hat{k}
\end{aligned} \tag{110}$$

In terms of the calculation of the moments produced by the controls, the moment arm is also altered by the flexible effects. For small displacements of the beams relative to their lengths, the new moment arms become

$$\begin{aligned}
\mathbf{r}_{canard} &= \left(\sqrt{x_{canard}^2 - (\Phi_f(x_{canard}) \eta_{f,1})^2}, \Phi_f(x_{canard}) \eta_{f,1} \right) \\
\mathbf{r}_{elev} &= \left(\sqrt{x_{elev}^2 + z_{elev}^2 - (z_e + \Phi_a(x_{elev}) \eta_{a,1})^2}, z_{elev} + \Phi_a(x_{elev}) \eta_{a,1} \right)
\end{aligned} \tag{111}$$

VIII. Results

The model has been linearized at $M = 8$ and at an altitude of 85,000 ft using velocity and flight path angle as outputs and elevator deflection and total temperature addition in the combustor as inputs. One point of interest that can be obtained from this simulation is the effect of the unsteady terms on the poles and zeros of the linearized system. Figure 2 shows a pole/zero map for the linearized rigid body system when unsteady effects are not included, while Fig. 3 shows the poles and zeros of the rigid body system when the unsteady effects are included. Clearly, the unsteady terms have a significant effect on the unstable pole and zero. Inclusion of the unsteady terms makes the system more unstable, while increasing the frequency of the non-minimum phase zero. The actual pole and zero locations are given in Table 1.

Unsteady OFF	Unsteady OFF	Unsteady ON	Unsteady ON
Poles	Zeros	Poles	Zeros
$-0.000137 \pm j0.023358$	1.8694	$-0.000151 \pm j0.02332$	2.64
0.8729	-1.8694	1.125	-2.64
-0.9159	0	-1.216	0
-.00107	N/A	-.001027	N/A

Table 1. Poles and Zeros of the Rigid Linearized System.

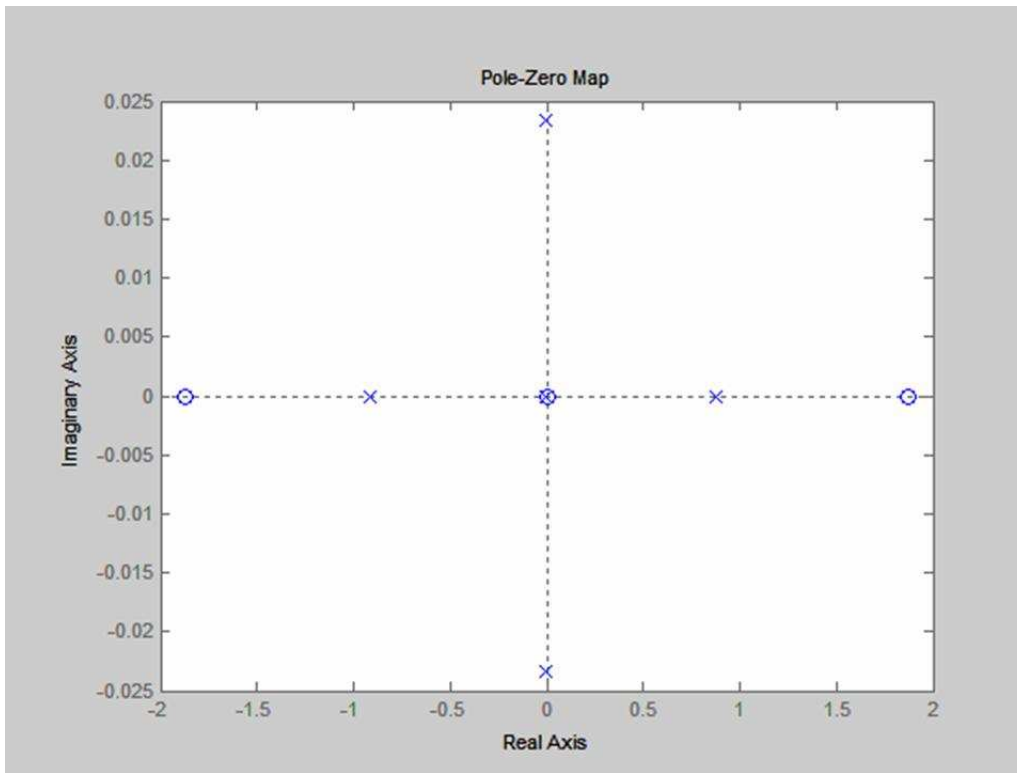


Figure 2. Poles and Zeros of Linearized Rigid Body System - Unsteady Effects Off.

Now, the flexible effects are included in the vehicle model. Figure 4 shows a pole/zero map for the flexible vehicle when unsteady effects are not included. Figures 5 and 6 show pole/zero maps when the unsteady effects are included. The difference here is that the stability derivatives due to $\dot{\eta}_{f,1}$ and $\dot{\eta}_{a,1}$ are included in Fig. 6 while they are not in the results shown in Fig. 5. In tabular form, the poles and zeros are shown in Table 2.

It can be seen that the unsteady effects, computed using piston theory, significantly change the poles and

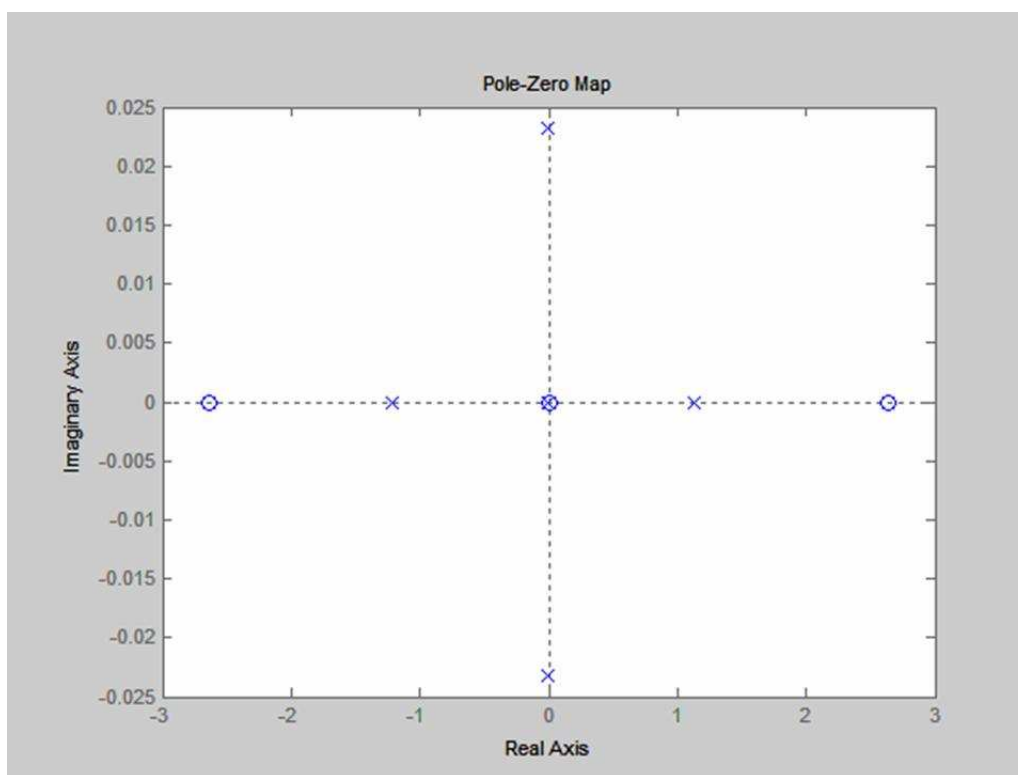


Figure 3. Poles and Zeros of Linearized Rigid Body System - Unsteady Effects On.

All Unsteady OFF	
Poles	Zeros
$-.538 \pm j26.909$	$-.538 \pm j26.904$
$-.36 \pm j17.99$	$-.36 \pm j17.99$
1.23	2.64
-1.32	-2.64
-.00088	0
$-.00012 \pm j.024$	N/A

Table 2. Poles and Zeros of the Flexible Linearized System With All Unsteady Effects Off.

Unsteady On & Unsteady Flex. OFF	
Poles	Zeros
$-.538 \pm j26.91$	$-.538 \pm j26.91$
$-.36 \pm j17.99$	$-.36 \pm j17.99$
1.88	3.88
-2.06	-3.88
-.00086	0
$-.00012 \pm j.024$	N/A

Table 3. Poles and Zeros of the Flexible Linearized System With Unsteady Effects On and Flexible Unsteady Effects Off.

Unsteady On & Unsteady Flex. ON	
Poles	Zeros
$-.55 \pm j26.91$	$-.56 \pm j26.89$
$-.36 \pm j17.99$	$-.36 \pm j17.99$
1.88	3.88
-2.06	-3.88
-.00086	0
$-.00012 \pm j.024$	N/A

Table 4. Poles and Zeros of the Flexible Linearized System With Unsteady Effects On and Flexible Unsteady Effects On.

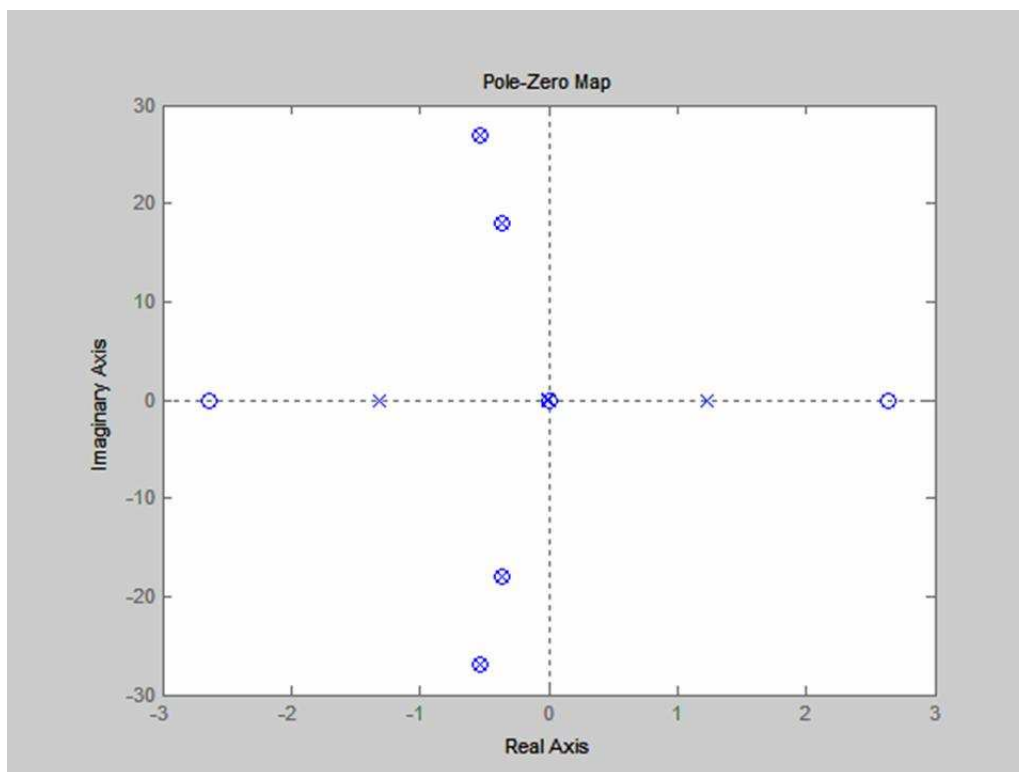


Figure 4. Poles and Zeros of Linearized Flexible System - Unsteady Effects Off.

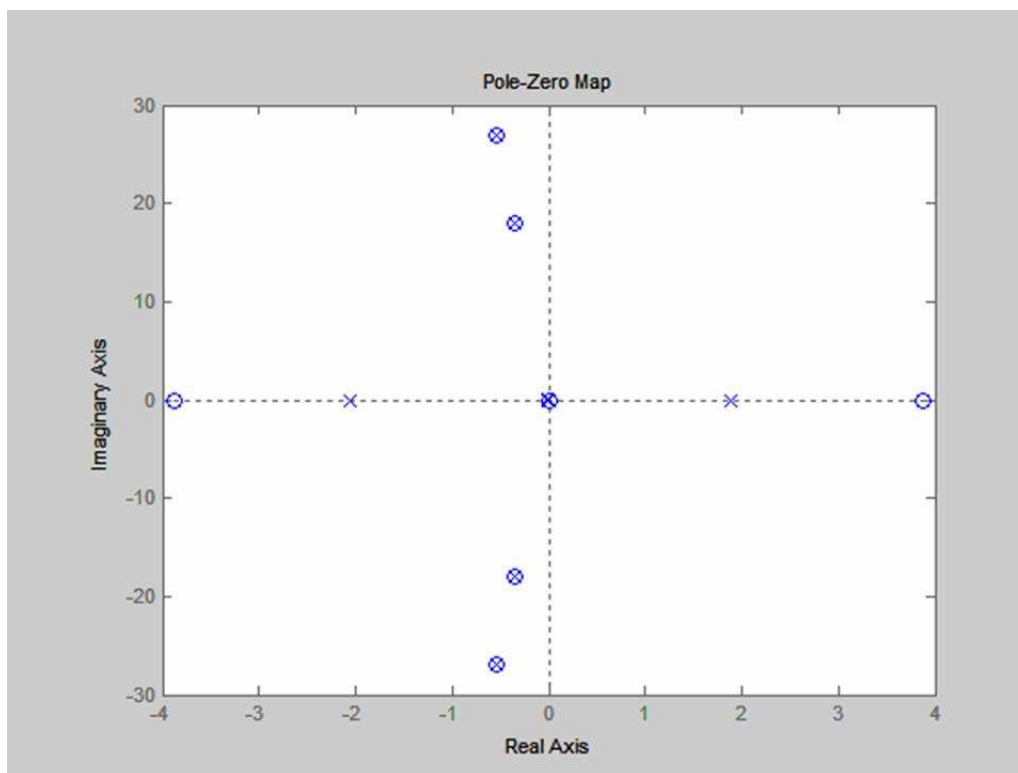


Figure 5. Poles and Zeros of Linearized Flexible System - Unsteady Effects On, Unsteady Flexible Effects Off.

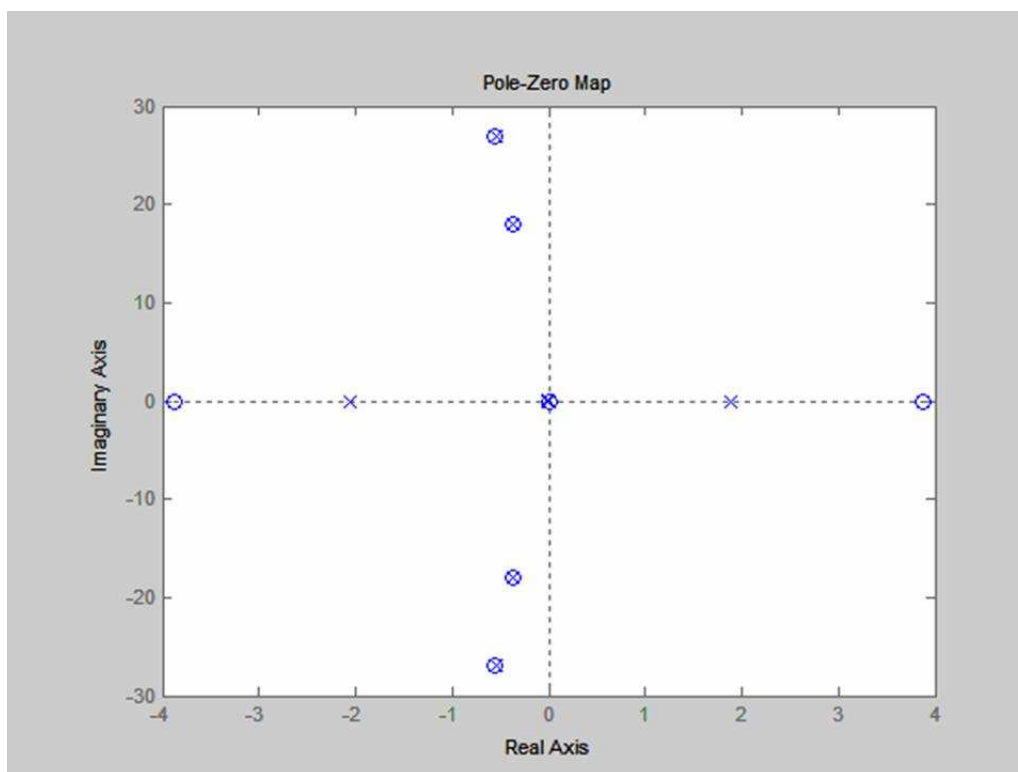


Figure 6. Poles and Zeros of Linearized Flexible System - Unsteady Effects On, Unsteady Flexible Effects On.

zeros of the linearized system. Both the unstable pole and zero of the linearized system move farther to the right in the s-plane when the unsteady effects are included. Only a slight change in pole and zero locations is observed when the unsteady effects due to $\dot{\eta}$ are included.

Figures 7, 8, and 9 show the lift force, drag force, and pitching moment for a one second run of the nonlinear simulation. Again, it can be seen that the unsteady effects are significant and are worth including in the nonlinear simulation.

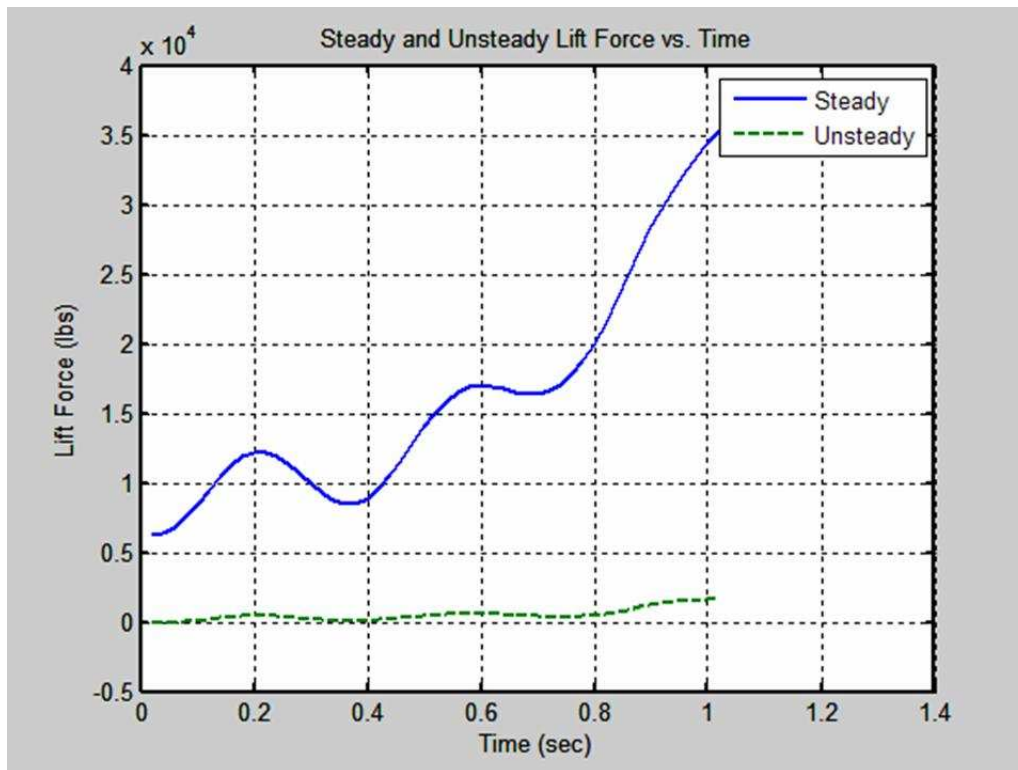


Figure 7. Lift Force (lbs).

IX. Conclusions

In this work, piston theory is used to develop a model for the longitudinal dynamics of a 2-dimensional hypersonic vehicle model. In particular, velocities of flow normal to the surface of the vehicle are used in a first order piston theory framework to determine the pressures on the surfaces of the vehicle. The pressures are then integrated over the body to determine the forces acting on the vehicle. Piston theory is useful here because it allows the inclusion of unsteady aerodynamic effects. Initial analysis has shown that the unsteady effects are significant.

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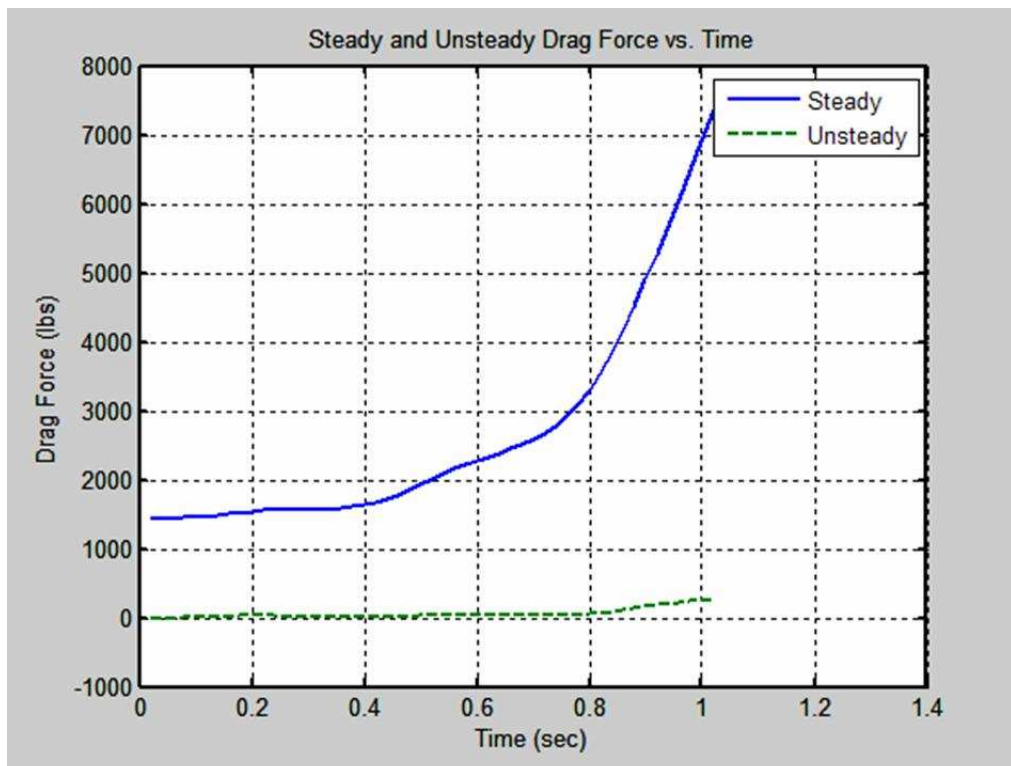


Figure 8. Drag Force (lbs).

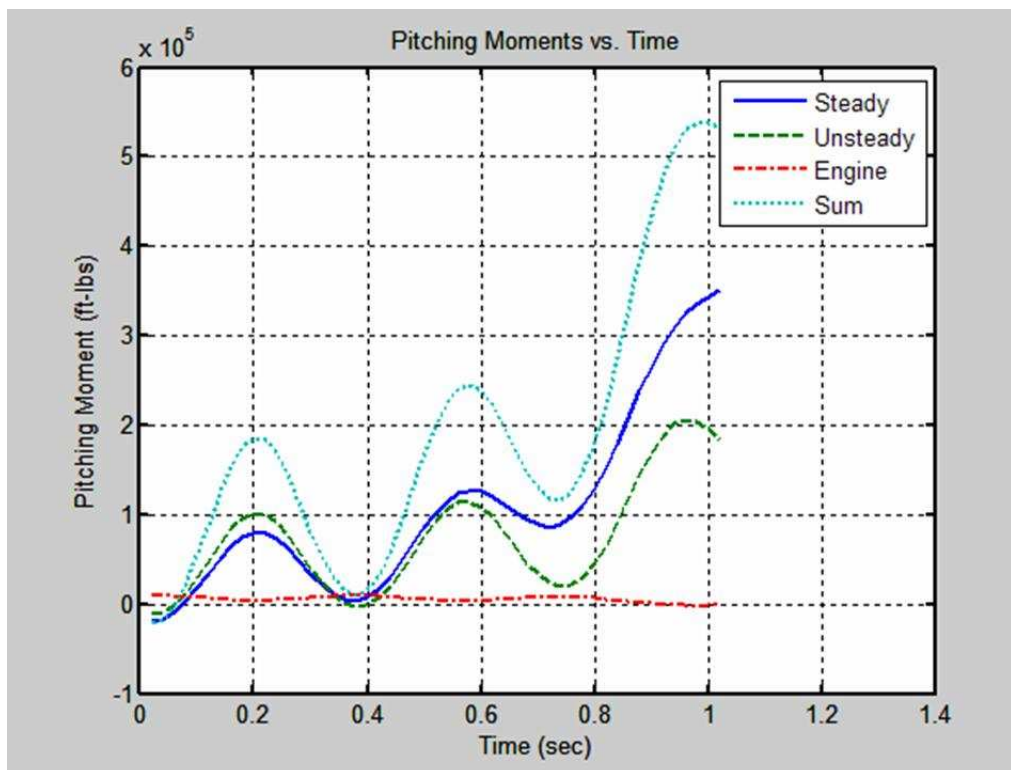


Figure 9. Pitching Moment (ft-lbs).

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⁶Bolender, M. A. and Doman, D. B., “A Non-Linear Model for the Longitudinal Dynamics of a Hypersonic Airbreathing Vehicle,” *Proceedings of the 2005 Guidance, Navigation and Control Conference*, AIAA Paper No. 2005-6255, August 2005.

⁷Bolender, M. A. and Doman, D. B., “Flight Path Angle Dynamics of Air-Breathing Hypersonic Vehicles,” *Proceedings of the 2006 AIAA Guidance, Navigation, and Control Conference*, AIAA-2006-6692, August 2006.

⁸Meirovitch, L., *Analytical Methods in Vibrations*, The Macmillan Company, New York, NY, 1967.

A. Flexible Effects

From Eq. 87

$$\begin{aligned}
N_{f,1}(t) = & \frac{A_{f,1}P_{cf}}{\beta_{f,1}} \left[\left(-\sin\{\beta_{f,1}\bar{x}_f\} + \sinh\{\beta_{f,1}\bar{x}_f\} \right) \left(\cos\{\beta_{f,1}\bar{x}_f\} + \cosh\{\beta_{f,1}\bar{x}_f\} - 2 \right) \right. \\
& \left. + \frac{A_{f,1}P_{cf}}{\beta_{f,1}} \left[\left(\cos\{\beta_{f,1}\bar{x}_f\} + \cosh\{\beta_{f,1}\bar{x}_f\} \right) \left(\sin\{\beta_{f,1}\bar{x}_f\} - \sinh\{\beta_{f,1}\bar{x}_f\} \right) \right] \right. \\
& + \frac{A_{f,1}P_{cd}}{\beta_{f,1}} \left[\left(-\sin\{\beta_{f,1}\bar{x}_f\} + \sinh\{\beta_{f,1}\bar{x}_f\} \right) \left(\cos\{\beta_{f,1}\bar{x}_f\} - \cos\{\beta_{f,1}(\bar{x}_f - L_f)\} \right) + \cosh\{\beta_{f,1}\bar{x}_f\} - \cosh\{\beta_{f,1}(\bar{x}_f - L_f)\} \right] \\
& \left. + \frac{A_{f,1}P_{cd}}{\beta_{f,1}} \left[\left(\cos\{\beta_{f,1}\bar{x}_f\} + \cosh\{\beta_{f,1}\bar{x}_f\} \right) \left(\sin\{\beta_{f,1}\bar{x}_f\} - \sin\{\beta_{f,1}(\bar{x}_f - L_f)\} \right) - \sinh\{\beta_{f,1}\bar{x}_f\} + \sinh\{\beta_{f,1}(\bar{x}_f - L_f)\} \right] \right] \\
& + (P_{cU} - P_{cL}) L_c A_{f,1} \left[\left(\sin\beta_{f,1}\bar{x}_f - \sinh\beta_{f,1}\bar{x}_f \right) \left(\sin\beta_{f,1}x_{canard} - \sinh\beta_{f,1}x_{canard} \right) + \left(\cos\beta_{f,1}\bar{x}_f + \cosh\beta_{f,1}\bar{x}_f \right) \left(\cos\beta_{f,1}x_{canard} - \cosh\beta_{f,1}x_{canard} \right) \right] \\
& \quad \quad \quad (112)
\end{aligned}$$

$$\begin{aligned}
N_{a,1}(t) = & \frac{2A_{a,1}P_{cf}}{\beta_{a,1}} \left(\sin\beta_{a,1}\bar{x}_a - \sinh\beta_{a,1}\bar{x}_a \right) \\
& + A_{a,1}C_1C_3 \left[\frac{1}{\beta_{a,1}^2} \sin\beta_{a,1}\bar{x}_a - \frac{\bar{x}_a}{\beta_{a,1}} \cos\beta_{a,1}\bar{x}_a - \frac{1}{\beta_{a,1}^2} \sin(\beta_{a,1}(\bar{x}_a - L_a)) + \frac{\bar{x}_a - L_a}{\beta_{a,1}} \cos(\beta_{a,1}(\bar{x}_a - L_a)) \right] \\
& \quad \quad \quad + \frac{A_{a,1}C_1C_4}{\beta_{a,1}} \left[\cos\beta_{a,1}\bar{x}_a - \cos(\beta_{a,1}(\bar{x}_a - L_a)) \right] \\
& + A_{a,1}C_1C_3 \left[\frac{-\bar{x}_a}{\beta_{a,1}} \cosh\beta_{a,1}\bar{x}_a + \frac{1}{\beta_{a,1}^2} \sinh\beta_{a,1}\bar{x}_a + \frac{1}{\beta_{a,1}} (\bar{x}_a - L_a) \cosh(\beta_{a,1}(\bar{x}_a - L_a)) - \frac{1}{\beta_{a,1}^2} \sinh(\beta_{a,1}(\bar{x}_a - L_a)) \right] \\
& \quad \quad \quad + \frac{A_{a,1}C_1C_4}{\beta_{a,1}} \left[\cosh\beta_{a,1}\bar{x}_a - \cosh(\beta_{a,1}(\bar{x}_a - L_a)) \right] \\
& + A_{a,1}C_2C_3 \left[\frac{1}{\beta_{a,1}^2} \cos\beta_{a,1}\bar{x}_a + \frac{\bar{x}_a}{\beta_{a,1}} \sin\beta_{a,1}\bar{x}_a - \frac{1}{\beta_{a,1}^2} \cos(\beta_{a,1}(\bar{x}_a - L_a)) - \frac{\bar{x}_a - L_a}{\beta_{a,1}} \sin(\beta_{a,1}(\bar{x}_a - L_a)) \right] \\
& \quad \quad \quad - \frac{A_{a,1}C_2C_4}{\beta_{a,1}} \left[\sin\beta_{a,1}\bar{x}_a - \sin(\beta_{a,1}(\bar{x}_a - L_a)) \right] \\
& + A_{a,1}C_2C_3 \left[\frac{-\bar{x}_a}{\beta_{a,1}} \sinh\beta_{a,1}\bar{x}_a + \frac{1}{\beta_{a,1}^2} \cosh\beta_{a,1}\bar{x}_a + \frac{(\bar{x}_a - L_a)}{\beta_{a,1}} \sinh(\beta_{a,1}(\bar{x}_a - L_a)) - \frac{1}{\beta_{a,1}^2} \cosh(\beta_{a,1}(\bar{x}_a - L_a)) \right] \\
& \quad \quad \quad + \frac{A_{a,1}C_2C_4}{\beta_{a,1}} \left[\sin\beta_{a,1}\bar{x}_a - \sinh(\beta_{a,1}(\bar{x}_a - L_a)) \right] \\
& + A_{a,1}(P_{eU} - P_{eL}) L_e \left[\left(\sin\beta_{a,1}\bar{x}_a - \sinh\beta_{a,1}\bar{x}_a \right) \left(\sin\beta_{a,1}x_{elev} - \sinh\beta_{a,1}x_{elev} \right) + \left(\cos\beta_{a,1}\bar{x}_a + \cosh\beta_{a,1}\bar{x}_a \right) \left(\cos\beta_{a,1}x_{elev} - \cosh\beta_{a,1}x_{elev} \right) \right] \\
& \quad \quad \quad (113)
\end{aligned}$$

where

$$\begin{aligned}
C_1 &= \sin\beta_{a,1}\bar{x}_a - \sinh\beta_{a,1}\bar{x}_a \\
C_2 &= \cos\beta_{a,1}\bar{x}_a + \cosh\beta_{a,1}\bar{x}_a \\
C_3 &= \frac{P_\infty - P_e}{-L_a} \\
C_4 &= C_3(L_a - \bar{x}_a) - P_e
\end{aligned} \tag{114}$$

From Eq. 97

$$\begin{aligned}
\frac{\partial C_M}{\partial \dot{\eta}_{f,1}} = & \frac{2A_{f,1}\rho_{cf}a_{cf}\sin\tau_{1,U}\tan\tau_{1,U}}{\beta_{f,1}^2q_\infty S\bar{c}} [1 - \cos\beta_{f,1}\bar{x}_f + \cos\beta_{f,1}\bar{x}_f \cosh\beta_{f,1}\bar{x}_f - \cosh\beta_{f,1}\bar{x}_f - \bar{x}_f\beta_{f,1} (\sin\beta_{f,1}\bar{x}_f - \sinh\beta_{f,1}\bar{x}_f)] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\sin\tau_{1,L}\tan\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [2 - \cos\beta_{f,1}L_f + \beta_{f,1}(\bar{x}_f - L_f)\sin\beta_{f,1}L_f + 2\cos\beta_{f,1}\bar{x}_f \cosh\beta_{f,1}\bar{x}_f] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\sin\tau_{1,L}\tan\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [\beta_{f,1}(\bar{x}_f - L_f)(\sin\beta_{f,1}\bar{x}_f \cosh\beta_{f,1}(\bar{x}_f - L_f) + \cos\beta_{f,1}\bar{x}_f \sinh\beta_{f,1}(\bar{x}_f - L_f))] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\sin\tau_{1,L}\tan\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [-\sin\beta_{f,1}\bar{x}_f \sinh\beta_{f,1}(\bar{x}_f - L_f) - \cos\beta_{f,1}\bar{x}_f \cosh\beta_{f,1}(\bar{x}_f - L_f)] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\sin\tau_{1,L}\tan\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [\sinh\beta_{f,1}\bar{x}_f \sin\beta_{f,1}(\bar{x}_f - L_f) - \cosh\beta_{f,1}\bar{x}_f \cos\beta_{f,1}(\bar{x}_f - L_f)] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\sin\tau_{1,L}\tan\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [-\beta_{f,1}(\bar{x}_f - L_f)\sinh\beta_{f,1}\bar{x}_f \cos\beta_{f,1}(\bar{x}_f - L_f) - \beta_{f,1}(\bar{x}_f - L_f)\cosh\beta_{f,1}\bar{x}_f \sin\beta_{f,1}(\bar{x}_f - L_f)] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\sin\tau_{1,L}\tan\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [-\beta_{f,1}(\bar{x}_f - L_f)\sinh\beta_{f,1}L_f - \cosh\beta_{f,1}L_f] \\
& - \frac{A_{f,1}\rho_{cd}a_{cd}\sin\tau_{1,L}\tan\tau_{1,L}\bar{x}_f}{\beta_{f,1}q_\infty S\bar{c}} [(\sin\beta_{f,1}\bar{x}_f - \sinh\beta_{f,1}\bar{x}_f)(\cos\beta_{f,1}(\bar{x}_f - L_f) + \cosh\beta_{f,1}(\bar{x}_f - L_f))] \\
& - \frac{A_{f,1}\rho_{cd}a_{cd}\sin\tau_{1,L}\tan\tau_{1,L}\bar{x}_f}{\beta_{f,1}q_\infty S\bar{c}} [(\cos\beta_{f,1}\bar{x}_f + \cosh\beta_{f,1}\bar{x}_f)(-\sin\beta_{f,1}(\bar{x}_f - L_f) + \sinh\beta_{f,1}(\bar{x}_f - L_f))] \\
& + \frac{2A_{f,1}\rho_{cf}a_{cf}\cos\tau_{1,U}}{\beta_{f,1}^2q_\infty S\bar{c}} [1 - \cos\beta_{f,1}\bar{x}_f + \cos\beta_{f,1}\bar{x}_f \cosh\beta_{f,1}\bar{x}_f - \cosh\beta_{f,1}\bar{x}_f] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\cos\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [2 - \cos\beta_{f,1}L_f + \beta_{f,1}(\bar{x}_f - L_f)\sin\beta_{f,1}L_f + 2\cos\beta_{f,1}\bar{x}_f \cosh\beta_{f,1}\bar{x}_f] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\cos\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [\beta_{f,1}(\bar{x}_f - L_f)(\sin\beta_{f,1}\bar{x}_f \cosh\beta_{f,1}(\bar{x}_f - L_f) + \cos\beta_{f,1}\bar{x}_f \sinh\beta_{f,1}(\bar{x}_f - L_f))] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\cos\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [-\sin\beta_{f,1}\bar{x}_f \sinh\beta_{f,1}(\bar{x}_f - L_f) - \cos\beta_{f,1}\bar{x}_f \cosh\beta_{f,1}(\bar{x}_f - L_f)] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\cos\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [\sinh\beta_{f,1}\bar{x}_f \sin\beta_{f,1}(\bar{x}_f - L_f) - \cosh\beta_{f,1}\bar{x}_f \cos\beta_{f,1}(\bar{x}_f - L_f)] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\cos\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [-\beta_{f,1}(\bar{x}_f - L_f)\sinh\beta_{f,1}\bar{x}_f \cos\beta_{f,1}(\bar{x}_f - L_f) - \beta_{f,1}(\bar{x}_f - L_f)\cosh\beta_{f,1}\bar{x}_f \sin\beta_{f,1}(\bar{x}_f - L_f)] \\
& + \frac{A_{f,1}\rho_{cd}a_{cd}\cos\tau_{1,L}}{\beta_{f,1}^2q_\infty S\bar{c}} [-\beta_{f,1}(\bar{x}_f - L_f)\sinh\beta_{f,1}L_f - \cosh\beta_{f,1}L_f]
\end{aligned} \tag{115}$$

From Eq. 98

$$\begin{aligned}
\frac{\partial C_Z}{\partial \dot{\eta}_{a,1}} &= \frac{-2\rho_{cf}a_{cf} \cos(\tau_{1,U} + \tau_2) A_{a,1}}{q_\infty S \beta_{a,1}} [\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a] \\
&- \frac{1}{q_\infty S \beta_{a,1}} [(f_1 \bar{x}_a^2 + g_1 \bar{x}_a + h_1) \cos \beta_{a,1} \bar{x}_a + (f_1 k_1^2 + g_1 k_1 + h_1) \cos(\beta_{a,1} k_1)] \\
&+ \frac{1}{q_\infty S \beta_{a,1}^2} (2f_1 \bar{x}_a + g_1) \sin \beta_{a,1} \bar{x}_a - \frac{2f_1 k_1 + g_1}{q_\infty S \beta_{a,1}} \sin \beta_{a,1} k_1 + \frac{2f_1}{q_\infty S \beta_{a,1}^3} (\cos \beta_{a,1} \bar{x}_a - \cos \beta_{a,1} k_1) \\
&- \frac{1}{q_\infty S \beta_{a,1}} \left[(f_1 \bar{x}_a^2 + g_1 \bar{x}_a + h_1) \cosh \beta_{a,1} \bar{x}_a - \frac{1}{\beta_{a,1}} (2f_1 \bar{x}_a + g_1) \sinh \beta_{a,1} \bar{x}_a + \frac{2f_1}{\beta_{a,1}^2} \cosh \beta_{a,1} \bar{x}_a \right] \\
&+ \frac{1}{q_\infty S \beta_{a,1}} \left[(f_1 k_1^2 + g_1 k_1 + h_1) \cosh \beta_{a,1} k_1 - \frac{1}{\beta_{a,1}} (2f_1 k_1 + g_1) \sinh \beta_{a,1} k_1 + \frac{2f_1}{\beta_{a,1}^2} \cosh \beta_{a,1} k_1 \right] \\
&+ \frac{1}{q_\infty S \beta_{a,1}} \left[(f_1 \bar{x}_a^2 + g_1 \bar{x}_a + h_1) \sin \beta_{a,1} \bar{x}_a + \frac{1}{\beta_{a,1}} (2f_1 \bar{x}_a + g_1) \cos \beta_{a,1} \bar{x}_a - \frac{1}{\beta_{a,1}} 2f_1 \sin \beta_{a,1} \bar{x}_a \right] \\
&- \frac{1}{q_\infty S \beta_{a,1}} \left[(f_1 k_1^2 + g_1 k_1 + h_1) \sin \beta_{a,1} \bar{x}_a - \frac{1}{\beta_{a,1}} (2f_1 k_1 + g_1) \cos \beta_{a,1} k_1 - \frac{1}{\beta_{a,1}} 2f_1 \sin \beta_{a,1} k_1 \right] \\
&+ \frac{1}{q_\infty S \beta_{a,1}} \left[- (f_1 \bar{x}_a^2 + g_1 \bar{x}_a + h_1) \sinh \beta_{a,1} \bar{x}_a + \frac{1}{\beta_{a,1}} (2f_1 \bar{x}_a + g_1) \cosh \beta_{a,1} \bar{x}_a - \frac{1}{\beta_{a,1}} 2f_1 \sinh \beta_{a,1} \bar{x}_a \right] \\
&+ \frac{1}{q_\infty S \beta_{a,1}} \left[(f_1 k_1^2 + g_1 k_1 + h_1) \sinh \beta_{a,1} \bar{x}_a - \frac{1}{\beta_{a,1}} (2f_1 k_1 + g_1) \cosh \beta_{a,1} k_1 - \frac{1}{\beta_{a,1}} 2f_1 \sinh \beta_{a,1} k_1 \right]
\end{aligned} \tag{116}$$

where

$$\begin{aligned}
k_1 &= \bar{x}_a - L_a \\
f_1 &= \rho_a a_a (\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) \\
g_1 &= (\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) (-a_a \rho_a \{L_a - \bar{x}_a\} + a_a \rho_e) (-a_a \rho_a \{L_a - \bar{x}_a\} + a_e \rho_a) \\
h_1 &= (\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) (-\rho_a \{L_a - \bar{x}_a\} + \rho_e) (-a_a \{L_a - \bar{x}_a\} + a_e) \\
\rho_a &= \frac{\rho_\infty - \rho_e}{-L_a} \\
a_a &= \frac{a_\infty - a_e}{-L_a}
\end{aligned} \tag{117}$$

From Eq. 99

$$\begin{aligned}
\frac{\partial CM}{\partial \dot{\eta}_{a,1} P_1} &= \frac{2\rho_{cf} a_{cf} A_{a,1} \sin \tau_{1,U} \tan \tau_{1,U}}{q_{\infty} S \bar{c}} \left[\frac{1}{\beta_{a,1}^2} \left\{ 1 + \cos \beta_{a,1} \bar{x}_a \cosh \beta_{a,1} \bar{x}_a - \cos \beta_{a,1} \bar{x}_a - \cosh \beta_{a,1} \bar{x}_a \right\} \right. \\
&\quad \left. + \frac{2\rho_{cf} a_{cf} A_{a,1} \sin \tau_{1,U} \tan \tau_{1,U}}{q_{\infty} S \bar{c}} \left[\frac{-\bar{x}_f}{\beta_{a,1}} \left\{ \sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a \right\} \right. \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_1 A_{a,1} (\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) \left[\frac{3\beta_{a,1}^2 \bar{x}_a^2 - 6}{\beta_{a,1}^4} \sin \beta_{a,1} \bar{x}_a - \frac{\beta_{a,1}^2 \bar{x}_a^3 - 6\bar{x}_a}{\beta_{a,1}^3} \cos \beta_{a,1} \bar{x}_a \right] \right. \\
&\quad \left. - \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_1 A_{a,1} (\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) \left[\frac{3\beta_{a,1}^2 (\bar{x}_a - L_a)^2 - 6}{\beta_{a,1}^4} \sin \beta_{a,1} (\bar{x}_a - L_a) - \frac{\beta_{a,1}^2 (\bar{x}_a - L_a)^3 - 6(\bar{x}_a - L_a)}{\beta_{a,1}^3} \cos \beta_{a,1} (\bar{x}_a - L_a) \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_1 A_{a,1} (\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) \left[-\frac{1}{\beta_{a,1}^4} (\beta_{a,1}^3 \bar{x}_a^3 \cosh \beta_{a,1} \bar{x}_a - 3\beta_{a,1}^2 \bar{x}_a^2 \sinh \beta_{a,1} \bar{x}_a + 6\beta_{a,1} \bar{x}_a \cosh \beta_{a,1} \bar{x}_a - 6 \sinh \beta_{a,1} \bar{x}_a) \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_1 A_{a,1} (\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) * \right. \\
&\quad \left. * \left[\frac{1}{\beta_{a,1}^4} (\beta_{a,1}^3 (\bar{x}_a - L_a)^3 \cosh \beta_{a,1} (\bar{x}_a - L_a) - 3\beta_{a,1}^2 (\bar{x}_a - L_a)^2 \sinh \beta_{a,1} (\bar{x}_a - L_a) + 6\beta_{a,1} (\bar{x}_a - L_a) \cosh \beta_{a,1} (\bar{x}_a - L_a) - 6 \sinh \beta_{a,1} (\bar{x}_a - L_a)) \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_1 A_{a,1} (\cos \beta_{a,1} \bar{x}_a - \cosh \beta_{a,1} \bar{x}_a) \left[\frac{3\beta_{a,1}^2 \bar{x}_a^2 - 6}{\beta_{a,1}^4} \cos \beta_{a,1} \bar{x}_a - \frac{\beta_{a,1}^2 \bar{x}_a^3 - 6\bar{x}_a}{\beta_{a,1}^3} \sin \beta_{a,1} \bar{x}_a \right] \right. \\
&\quad \left. - \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_1 A_{a,1} (\cos \beta_{a,1} \bar{x}_a - \cosh \beta_{a,1} \bar{x}_a) \left[\frac{3\beta_{a,1}^2 (\bar{x}_a - L_a)^2 - 6}{\beta_{a,1}^4} \cos \beta_{a,1} (\bar{x}_a - L_a) - \frac{\beta_{a,1}^2 (\bar{x}_a - L_a)^3 - 6(\bar{x}_a - L_a)}{\beta_{a,1}^3} \sin \beta_{a,1} (\bar{x}_a - L_a) \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_1 A_{a,1} (\cos \beta_{a,1} \bar{x}_a - \cosh \beta_{a,1} \bar{x}_a) \left[\frac{-1}{\beta_{a,1}^4} (\beta_{a,1}^3 \bar{x}_a^3 \sinh \beta_{a,1} \bar{x}_a - 3\beta_{a,1}^2 \bar{x}_a^2 \cosh \beta_{a,1} \bar{x}_a + 6\beta_{a,1} \bar{x}_a \sinh \beta_{a,1} \bar{x}_a - 6 \cosh \beta_{a,1} \bar{x}_a) \right] \right. \\
&\quad \left. - \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_1 A_{a,1} (\cos \beta_{a,1} \bar{x}_a - \cosh \beta_{a,1} \bar{x}_a) * \right. \\
&\quad \left. * \left[\frac{-1}{\beta_{a,1}^4} (\beta_{a,1}^3 (\bar{x}_a - L_a)^3 \sinh \beta_{a,1} (\bar{x}_a - L_a) - 3\beta_{a,1}^2 (\bar{x}_a - L_a)^2 \cosh \beta_{a,1} (\bar{x}_a - L_a) + 6\beta_{a,1} (\bar{x}_a - L_a) \sinh \beta_{a,1} (\bar{x}_a - L_a) - 6 \cosh \beta_{a,1} (\bar{x}_a - L_a)) \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_2 A_{a,1} \left[\frac{2\bar{x}_a}{\beta_{a,1}^2} \sin \beta_{a,1} \bar{x}_a - \frac{\beta_{a,1} \bar{x}_a^2 - 2}{\beta_{a,1}^3} \cos \beta_{a,1} \bar{x}_a - \left\{ \frac{2(\bar{x}_a - L_a)}{\beta_{a,1}^2} \sin \beta_{a,1} (\bar{x}_a - L_a) - \frac{\beta_{a,1} (\bar{x}_a - L_a)^2 - 2}{\beta_{a,1}^3} \cos \beta_{a,1} (\bar{x}_a - L_a) \right\} \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_2 A_{a,1} * \right. \\
&\quad * \left[\beta_{a,1}^2 \bar{x}_a^2 \cosh \beta_{a,1} \bar{x}_a - 2\beta_{a,1} \bar{x}_a \sinh \beta_{a,1} \bar{x}_a + 2 \cosh \beta_{a,1} \bar{x}_a - \left\{ \beta_{a,1}^2 (\bar{x}_a - L_a)^2 \cosh \beta_{a,1} (\bar{x}_a - L_a) - 2\beta_{a,1} (\bar{x}_a - L_a) \sinh \beta_{a,1} (\bar{x}_a - L_a) + 2 \cosh \beta_{a,1} (\bar{x}_a - L_a) \right\} \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_2 A_{a,1} \left[\frac{2\bar{x}_a \cos \beta_{a,1} \bar{x}_a}{\beta_{a,1}^2} + \frac{\beta_{a,1} \bar{x}_a^2 - 2}{\beta_{a,1}^3} \sin \beta_{a,1} \bar{x}_a - \left\{ \frac{2(\bar{x}_a - L_a) \cos \beta_{a,1} (\bar{x}_a - L_a)}{\beta_{a,1}^2} + \frac{\beta_{a,1} (\bar{x}_a - L_a)^2 - 2}{\beta_{a,1}^3} \sin \beta_{a,1} (\bar{x}_a - L_a) \right\} \right] \right. \\
&\quad \left. - \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_2 A_{a,1} \left[\beta_{a,1}^2 \bar{x}_a^2 \sinh \beta_{a,1} \bar{x}_a - 2\beta_{a,1} \bar{x}_a \cosh \beta_{a,1} \bar{x}_a + 2 \sinh \beta_{a,1} \bar{x}_a \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_2 A_{a,1} \left[\beta_{a,1}^2 (\bar{x}_a - L_a)^2 \sinh \beta_{a,1} (\bar{x}_a - L_a) - 2\beta_{a,1} (\bar{x}_a - L_a) \cosh \beta_{a,1} (\bar{x}_a - L_a) + 2 \sinh \beta_{a,1} (\bar{x}_a - L_a) \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_3 A_{a,1} \left[2 - \cos \beta_{a,1} L_a + \beta_{a,1} (\bar{x}_a - L_a) \sin \beta_{a,1} L_a + \beta_{a,1} (\bar{x}_a - L_a) \left\{ \sin \beta_{a,1} \bar{x}_a \cosh \beta_{a,1} (\bar{x}_a - L_a) + \cos \beta_{a,1} \bar{x}_a \sinh \beta_{a,1} (\bar{x}_a - L_a) \right\} \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_3 A_{a,1} \left[2 \cos \beta_{a,1} \bar{x}_a \cosh \beta_{a,1} \bar{x}_a - \sin \beta_{a,1} \bar{x}_a \sinh \beta_{a,1} (\bar{x}_a - L_a) - \cos \beta_{a,1} \bar{x}_a \cosh \beta_{a,1} (\bar{x}_a - L_a) + \sin \beta_{a,1} (\bar{x}_a - L_a) \sinh \beta_{a,1} \bar{x}_a \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_3 A_{a,1} \left[-\cos \beta_{a,1} (\bar{x}_a - L_a) \cosh \beta_{a,1} \bar{x}_a - \beta_{a,1} (\bar{x}_a - L_a) \cos \beta_{a,1} (\bar{x}_a - L_a) \sinh \beta_{a,1} \bar{x}_a \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_3 A_{a,1} \left[-\beta_{a,1} (\bar{x}_a - L_a) \sin \beta_{a,1} (\bar{x}_a - L_a) \cosh \beta_{a,1} \bar{x}_a - \beta_{a,1} (\bar{x}_a - L_a) \sinh \beta_{a,1} L_a - \cosh \beta_{a,1} L_a \right] \right. \\
&\quad \left. + \frac{\sin(\tau_{1,U} + \tau_2)}{q_{\infty} S \bar{c}} J_4 A_{a,1} * \right. \\
&\quad \left[(\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) (\cos \beta_{a,1} (\bar{x}_a - L_a) + \cosh \beta_{a,1} (\bar{x}_a - L_a)) + (\cos \beta_{a,1} \bar{x}_a + \cosh \beta_{a,1} \bar{x}_a) (-\sin \beta_{a,1} (\bar{x}_a - L_a) + \sinh \beta_{a,1} (\bar{x}_a - L_a)) \right] \\
&\quad + \frac{\rho_{cf} a_{cf} \cos \tau_{1,U} A_{a,1}}{q_{\infty} S \bar{c} \beta_{a,1}^2} \left[(\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) (\sin \beta_{a,1} \bar{x}_a - \beta_{a,1} \bar{x}_a \cos \beta_{a,1} \bar{x}_a - \beta_{a,1} \bar{x}_a \cosh \beta_{a,1} \bar{x}_a + \sinh \beta_{a,1} \bar{x}_a) \right] \\
&\quad + \frac{\rho_{cf} a_{cf} \cos \tau_{1,U} A_{a,1}}{q_{\infty} S \bar{c} \beta_{a,1}^2} \left[(\cos \beta_{a,1} \bar{x}_a + \cosh \beta_{a,1} \bar{x}_a) (\cos \beta_{a,1} \bar{x}_a + \beta_{a,1} \bar{x}_a \sin \beta_{a,1} \bar{x}_a - \beta_{a,1} \bar{x}_a \sinh \beta_{a,1} \bar{x}_a + \cosh \beta_{a,1} \bar{x}_a - 2) \right]
\end{aligned}$$

(118)

Continued from Eq. 99

$$\begin{aligned}
\frac{\partial C_M}{\partial \dot{\eta}_{a,1} P_2} &= \frac{\rho_a a_a \cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} A_{a,1} (\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) \left[\frac{3\beta_{a,1}^2 \bar{x}_a^2 - 6}{\beta_{a,1}^4} \sin \beta_{a,1} \bar{x}_a - \frac{\beta_{a,1}^2 \bar{x}_a^3 - 6\bar{x}_a}{\beta_{a,1}^3} \cos \beta_{a,1} \bar{x}_a \right] \\
&- \frac{\rho_a a_a \cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} A_{a,1} (\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) \left[\frac{3\beta_{a,1}^2 (\bar{x}_a - L_a)^2 - 6}{\beta_{a,1}^4} \sin \beta_{a,1} (\bar{x}_a - L_a) - \frac{\beta_{a,1}^2 (\bar{x}_a - L_a)^3 - 6(\bar{x}_a - L_a)}{\beta_{a,1}^3} \cos \beta_{a,1} (\bar{x}_a - L_a) \right] \\
&+ \frac{\rho_a a_a \cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} A_{a,1} (\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) \left[-\frac{1}{\beta_{a,1}^4} (\beta_{a,1}^3 \bar{x}_a^3 \cosh \beta_{a,1} \bar{x}_a - 3\beta_{a,1}^2 \bar{x}_a^2 \sinh \beta_{a,1} \bar{x}_a + 6\beta_{a,1} \bar{x}_a \cosh \beta_{a,1} \bar{x}_a - 6 \sinh \beta_{a,1} \bar{x}_a) \right. \\
&\quad \left. + \frac{\rho_a a_a \cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} A_{a,1} (\sin \beta_{a,1} \bar{x}_a - \sinh \beta_{a,1} \bar{x}_a) * \right. \\
&\quad \left. * \left[\frac{1}{\beta_{a,1}^3} (\bar{x}_a - L_a)^3 \cosh \beta_{a,1} (\bar{x}_a - L_a) - 3\beta_{a,1}^2 (\bar{x}_a - L_a)^2 \sinh \beta_{a,1} (\bar{x}_a - L_a) + 6\beta_{a,1} (\bar{x}_a - L_a) \cosh \beta_{a,1} (\bar{x}_a - L_a) - 6 \sinh \beta_{a,1} (\bar{x}_a - L_a) \right] \right. \\
&\quad \left. + \frac{\rho_a a_a \cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} A_{a,1} (\cos \beta_{a,1} \bar{x}_a - \cosh \beta_{a,1} \bar{x}_a) \left[\frac{3\beta_{a,1}^2 \bar{x}_a^2 - 6}{\beta_{a,1}^4} \cos \beta_{a,1} \bar{x}_a - \frac{\beta_{a,1}^2 \bar{x}_a^3 - 6\bar{x}_a}{\beta_{a,1}^3} \sin \beta_{a,1} \bar{x}_a \right] \right. \\
&\quad \left. - \frac{\rho_a a_a \cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} A_{a,1} (\cos \beta_{a,1} \bar{x}_a - \cosh \beta_{a,1} \bar{x}_a) \left[\frac{3\beta_{a,1}^2 (\bar{x}_a - L_a)^2 - 6}{\beta_{a,1}^4} \cos \beta_{a,1} (\bar{x}_a - L_a) - \frac{\beta_{a,1}^2 (\bar{x}_a - L_a)^3 - 6(\bar{x}_a - L_a)}{\beta_{a,1}^3} \sin \beta_{a,1} (\bar{x}_a - L_a) \right] \right. \\
&\quad \left. + \frac{\rho_a a_a \cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} A_{a,1} (\cos \beta_{a,1} \bar{x}_a - \cosh \beta_{a,1} \bar{x}_a) \left[\frac{-1}{\beta_{a,1}^4} (\beta_{a,1}^3 \bar{x}_a^3 \sinh \beta_{a,1} \bar{x}_a - 3\beta_{a,1}^2 \bar{x}_a^2 \cosh \beta_{a,1} \bar{x}_a + 6\beta_{a,1} \bar{x}_a \sinh \beta_{a,1} \bar{x}_a - 6 \cosh \beta_{a,1} \bar{x}_a) \right. \right. \\
&\quad \left. \left. - \frac{\rho_a a_a \cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} A_{a,1} (\cos \beta_{a,1} \bar{x}_a - \cosh \beta_{a,1} \bar{x}_a) * \right. \right. \\
&\quad \left. \left. * \left[\frac{-1}{\beta_{a,1}^3} (\bar{x}_a - L_a)^3 \sinh \beta_{a,1} (\bar{x}_a - L_a) - 3\beta_{a,1}^2 (\bar{x}_a - L_a)^2 \cosh \beta_{a,1} (\bar{x}_a - L_a) + 6\beta_{a,1} (\bar{x}_a - L_a) \sinh \beta_{a,1} (\bar{x}_a - L_a) - 6 \cosh \beta_{a,1} (\bar{x}_a - L_a) \right] \right. \right. \\
&\quad \left. \left. + \frac{\cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} J_5 A_{a,1} \left[\frac{2\bar{x}_a}{\beta_{a,1}^2} \sin \beta_{a,1} \bar{x}_a - \frac{\beta_{a,1} \bar{x}_a^2 - 2}{\beta_{a,1}^3} \cos \beta_{a,1} \bar{x}_a - \left\{ \frac{2(\bar{x}_a - L_a)}{\beta_{a,1}^2} \sin \beta_{a,1} (\bar{x}_a - L_a) - \frac{\beta_{a,1} (\bar{x}_a - L_a)^2 - 2}{\beta_{a,1}^3} \cos \beta_{a,1} (\bar{x}_a - L_a) \right\} \right] \right. \right. \\
&\quad \left. \left. + \frac{\cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} J_5 A_{a,1} * \right. \right. \\
&\quad \left. \left. * \left[\beta_{a,1}^2 \bar{x}_a^2 \cosh \beta_{a,1} \bar{x}_a - 2\beta_{a,1} \bar{x}_a \sinh \beta_{a,1} \bar{x}_a + 2 \cosh \beta_{a,1} \bar{x}_a - \left\{ \beta_{a,1}^2 (\bar{x}_a - L_a)^2 \cosh \beta_{a,1} (\bar{x}_a - L_a) - 2\beta_{a,1} (\bar{x}_a - L_a) \sinh \beta_{a,1} (\bar{x}_a - L_a) + 2 \cosh \beta_{a,1} (\bar{x}_a - L_a) \right\} \right] \right. \right. \\
&\quad \left. \left. + \frac{\cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} J_5 A_{a,1} \left[\frac{2\bar{x}_a \cos \beta_{a,1} \bar{x}_a}{\beta_{a,1}^2} + \frac{\beta_{a,1}^2 \bar{x}_a^2 - 2}{\beta_{a,1}^3} \sin \beta_{a,1} \bar{x}_a - \left\{ \frac{2(\bar{x}_a - L_a) \cos \beta_{a,1} (\bar{x}_a - L_a)}{\beta_{a,1}^2} + \frac{\beta_{a,1}^2 (\bar{x}_a - L_a)^2 - 2}{\beta_{a,1}^3} \sin \beta_{a,1} (\bar{x}_a - L_a) \right\} \right] \right. \right. \\
&\quad \left. \left. - \frac{\cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} J_5 A_{a,1} \left[\beta_{a,1}^2 \bar{x}_a^2 \sinh \beta_{a,1} \bar{x}_a - 2\beta_{a,1} \bar{x}_a \cosh \beta_{a,1} \bar{x}_a + 2 \sinh \beta_{a,1} \bar{x}_a \right] \right. \right. \\
&\quad \left. \left. + \frac{\cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} J_5 A_{a,1} \left[\beta_{a,1}^2 (\bar{x}_a - L_a)^2 \sinh \beta_{a,1} (\bar{x}_a - L_a) - 2\beta_{a,1} (\bar{x}_a - L_a) \cosh \beta_{a,1} (\bar{x}_a - L_a) + 2 \sinh \beta_{a,1} (\bar{x}_a - L_a) \right] \right. \right. \\
&\quad \left. \left. + \frac{\cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} J_6 A_{a,1} \left[2 - \cos \beta_{a,1} L_a + \beta_{a,1} (\bar{x}_a - L_a) \sin \beta_{a,1} L_a + \beta_{a,1} (\bar{x}_a - L_a) \left\{ \sin \beta_{a,1} \bar{x}_a \cosh \beta_{a,1} (\bar{x}_a - L_a) + \cos \beta_{a,1} \bar{x}_a \sinh \beta_{a,1} (\bar{x}_a - L_a) \right\} \right] \right. \right. \\
&\quad \left. \left. + \frac{\cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} J_6 A_{a,1} \left[2 \cos \beta_{a,1} \bar{x}_a \cosh \beta_{a,1} \bar{x}_a - \sin \beta_{a,1} \bar{x}_a \sinh \beta_{a,1} (\bar{x}_a - L_a) - \cos \beta_{a,1} \bar{x}_a \cosh \beta_{a,1} (\bar{x}_a - L_a) + \sin \beta_{a,1} (\bar{x}_a - L_a) \sinh \beta_{a,1} \bar{x}_a \right] \right. \right. \\
&\quad \left. \left. + \frac{\cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} J_6 A_{a,1} \left[-\cos \beta_{a,1} (\bar{x}_a - L_a) \cosh \beta_{a,1} \bar{x}_a - \beta_{a,1} (\bar{x}_a - L_a) \cos \beta_{a,1} (\bar{x}_a - L_a) \sinh \beta_{a,1} \bar{x}_a \right] \right. \right. \\
&\quad \left. \left. + \frac{\cos(\tau_{1,U} + \tau_2)}{q_\infty S \bar{c}} J_6 A_{a,1} \left[-\beta_{a,1} (\bar{x}_a - L_a) \sin \beta_{a,1} (\bar{x}_a - L_a) \cosh \beta_{a,1} \bar{x}_a - \beta_{a,1} (\bar{x}_a - L_a) \sinh \beta_{a,1} L_a - \cosh \beta_{a,1} L_a \right] \right. \right. \\
&\quad \left. \left. (119) \right. \right.
\end{aligned}$$

where

$$\begin{aligned}
\frac{\partial C_M}{\partial \dot{\eta}_{a,1}} &= \frac{\partial C_M}{\partial \dot{\eta}_{a,1} P_1} + \frac{\partial C_M}{\partial \dot{\eta}_{a,1} P_2} \\
J_1 &= \rho_a a_a m_1 \\
J_2 &= -2k \rho_a a_a m_1 + \rho_a a_a \{m_1 \bar{x}_a + m_2\} + \{\rho_e a_a + \rho_a a_e\} m_1 \\
J_3 &= \rho_a a_a m_1 k^2 - 2k \rho_a a_a \{m_1 \bar{x}_a + m_2\} - \{\rho_e a_a + \rho_a a_e\} m_1 k + \{\rho_e a_a + \rho_a a_e\} \{m_1 \bar{x}_a + m_2\} + \rho_e a_e m_1 \\
J_4 &= \rho_a a_a \{m_1 \bar{x}_a + m_2\} k^2 - \{\rho_e a_a + \rho_a a_e\} \{m_1 \bar{x}_a + m_2\} k + \rho_e a_e \{m_1 \bar{x}_a + m_2\} \\
J_5 &= 2k \rho_a a_a + (\rho_e a_a + \rho_a a_e) \\
J_6 &= \rho_a a_a k^2 - k(\rho_e a_a \rho_a a_e) + \rho_e a_e \\
\rho_a &= \frac{\rho_\infty - \rho_e}{-L_a} \\
a_a &= \frac{a_\infty - a_e}{-L_a} \\
k &= L_a - \bar{x}_a \\
m_1 &= \tan(\tau_{1,U} + \tau_2) \\
m_2 &= -L \tan \tau_{1,U} \\
(121)
\end{aligned}$$